METHODOLOGY TO PRIORITIZE AND OPTIMIZE PASSIVE DESIGN STRATEGIES IN CONCEPTUAL DESIGN PHASE

Transforming early architectural workflow

Abstract

The following paper devises a step-by-step process/method to quickly optimize passive design strategies in the conceptual design phase in architectural practice. This study explores the potential capabilities of Sefaira, a cloud-based software platform for performance-based design, to achieve this purpose. The ultimate aim of the study is to determine what passive design strategies have the most impact on building energy consumption and daylight potential, prioritize them in decreasing order of impact, and devise a method for architects to make quick and impactful design decisions while developing conceptual designs hence integrating this process into their workflow.

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TABLE OF CONTENTS

INTRODUCTION

Background

Since the advent of the green building movement and the emergence of various building rating systems like LEED and Living Building Challenge in combination with stricter building codes, building performance simulation has become an integral part of the AEC industry. But these performance simulations are usually intended to be used to check compliance with the building code, design the mechanical systems, or achieve a credit in a building rating system, most of which occurs after the designs have been developed by the architects. This results in losing out on valuable opportunities in the early stages of building design to optimize passive design strategies like orientation, massing, window size and placement, and shading, which are known to have a significant impact on the energy and daylight performance at minimal additional cost in case of new buildings.

Prescriptive versus Performance-Based Approach

Traditional architectural practice involves using rules of thumb and personal experience to decide which passive design strategies work the best for their designs. Although the power of these rules gained through years of experience cannot be underestimated, it should be accepted that they have limitations owing to the uniqueness of each building in terms of its micro-climate, context, usage, or form. As a result, they might often lead to sub-optimal designs and are not flexible enough to provide insight into which strategy has the highest impact on performance. In other words, they are intended to be prescriptive rather than performance-based. Performance-based design shifts some time from the later design stages to the early ones thus setting the project on track early and reducing rework in later stages (Figure 1 top). It expands the role of analysis, using appropriate analysis to drive decisions in each stage (Figure 1 bottom). More information on this subject can be found at http://info.aia.org/EnergyModeling.aspx.

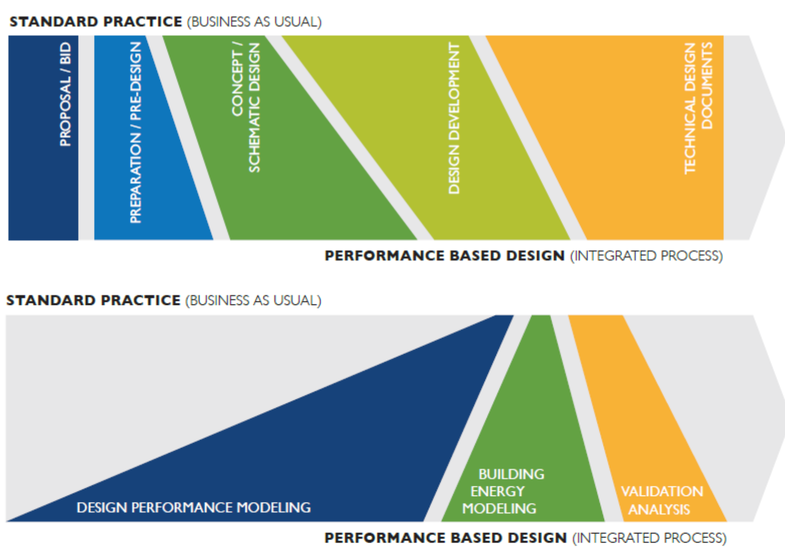


Figure 1: Standard Practice vs Performance Based Design (extracted from sefaira.com)

Even building codes are adding performance-based pathways over the past few years as they're more flexible and more results-driven than prescriptive compliance. California's Title 24 is moving toward its Net Zero Energy requirement, which takes effect in 2020. Part L is enforcing similar goals in the UK. In 2013, the International Energy Conservation Code (IECC) adopted a new performance-based compliance pathway that is already popular in many states. Passive House, which has long been associated with a prescriptive approach (a "Passive House envelope"), is also transitioning to a true performance-based standard based on both site and source energy metrics. The Passive House Institute US (PHIUS) is developing a series of climate-specific standards for different US climate zones (expected to be released early 2015) in recognition that a single prescriptive approach is not universally applicable. All these developments suggest a change in the traditional architectural practice.

Impact of Passive Design on Building Performance

Building shape/form along with the glazing typically influence the building energy use by a considerable amount. When daylight performance is also taken into account, we can create buildings that deliver a much better occupant experience, without much additional capital cost unlike bigger and better HVAC systems which come at a significant first cost. There is a compelling value proposition. Performance analysis used at this critical conceptual design stage would prove to be very useful to architects to aid in their decision-making. But most of the tools available to achieve this purpose require relatively detailed inputs which are not usually available at such early stage of the design, have long processing times, and do not provide real-time feedback to the designer. This results in outsourcing the job to modeling experts after each design option is complete but even this offers little help as the design proceeds at a greater speed than the performance modeling, hence losing out on a lot of valuable opportunities to modify design early. At these early stages of design, absolute performance estimates are not needed as much as the relative performance of various design options to determine optimal solutions. Hence, architectural firms are increasingly seeking ways to integrate easy-to-use and quick performance analysis tool(s) into their work-flow that can be used to quickly analyze and compare design options using some generic inputs if needed and provide continuous real-time feedback to make informed design decisions while they design.

The Functioning of the Architectural Practice

In typical architectural practice, the design process moves very fast in the early design phases as it is mainly focused on providing clients with design options frequently based on aesthetics and rules of thumb. It is also during these early phases many important design decisions are made which also have a great impact on performance and are difficult to change later. But toggling between applications to run performance simulations of one design at a time might not be the most efficient way to integrate the same into the workflow. Architects want to understand which design decision affects the building performance the most and hence need to be focused on, what are the biggest opportunities and constraints, how their design options compare, what are the optimal parameters for the most effective strategies, what is the responsiveness of the design to various passive strategies, what are the synergies and trade-offs among strategies, and even get some of their specific questions regarding a particular strategy answered. It is also worth noting that daylight performance and occupant comfort also weigh in as equally important factors along with energy performance for clients. Also important to the architects is an effective way to present these results to the client in a persuasive manner. Hence what they seek for is a performance analysis methodology and tool(s) that can potentially become an integral part of the design process to achieve all of the above without deviating much from their usual workflow, and ultimately position themselves in the green building market by aiming to achieve increasingly stringent performance expectations like those by LEED or ambitious targets like 2030 Challenge.

OBJECTIVE/ GOAL

Objective

The overarching objective of the study is to devise a methodology for architects to use energy and daylight performance analysis tools in the conceptual phase of building design to take maximum advantage of the benefits of passive building design (design approach that uses natural elements, often sunlight, to heat, cool, or light a building). Since daylight is usually considered as critical as energy use in building types like offices and schools more than any other building type, a new office building in Minneapolis is chosen as the subject of study to demonstrate the methodology described in the later section.

Before going forward with integrating any performance analysis tools into the workflow, it is important to set a goal that is intended to be achieved as a result of the analysis, like 2030 Challenge for energy performance, LEED credit for minimum and maximum daylight levels, meeting ASHRAE standard 90.1 etc., or even just achieving a very narrow objective like optimum window to wall area ratio.

Broader Goal

For this demonstrative study, the broader goal is to explore the interactions - tradeoffs and synergies - between energy and daylight performance, test the potential of a well day-lit building using just passive design strategies to achieve 2030 Challenge, and also question the rules of thumb. Many design decisions in the early design phases that affect both energy use and daylight usually result in trade-offs between the two unless an optimum solution is found that can lead to synergies between the two by utilizing the benefits of better daylight in reducing the lighting energy use and/or cooling energy use. This is a challenge in itself as these interactions can be complex. Good daylight could possibly lower lighting energy by using proper daylight controls, as well as lower cooling energy by avoiding the heat produced by the electric lights that can now be turned off due to better daylight. But higher glazing can also lead to more unwanted solar gain in the summer thus increasing cooling energy use, and also cause more heat loss thus increasing the heating energy use in the winter. Also, more glazing leads to more glare unless proper shading techniques are in place. These interactions vary a lot depending on the climate, context, building shape and other factors which is why rules of thumb might not work in all cases if their basis could not be justified well. Hence, analyzing these interactions provides an opportunity for well-designed glazing to simultaneously improve daylighting, enhance occupant comfort, and reduce energy use, operating cost, and may be even mechanical system size.

Specific Goals

The specific goals in the order of priority are: 1) Maximize well-lit space/Spatial Daylight Autonomy/sDA (>55% floor area) to earn points under LEED v4, 2) Minimize glare/ Annual Sun Exposure/ ASE (<10% floor area) to earn points under LEED v4 if possible, or atleast keep it within manageable limits which in itself is a challenging task since ASE and sDA move in the same direction, and 3) Lower energy use to meet 2030 challenge (<27 kBTU/sf/yr) since the fundamental design moves to address the first two goals often have a significant impact on energy use. The terminology/ metrics used for each is described in the next section.

TERMINOLOGY

Dynamic Daylighting Metrics

Dynamic daylighting metrics are location-based and annualized. The USGBC codified two of these metrics in LEED v4: Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE).

Spatial Daylight Autonomy (sDA) describes how much of a space receives sufficient daylight. Specifically, it describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours.

Annual Sun Exposure (ASE) describes how much of space receives too much direct sunlight, which can cause visual discomfort (glare) or increase cooling loads. Specifically, ASE measures the percentage of floor area that receives at least 1000 lux for at least 250 occupied hours per year.

Both these metrics must be considered together for a clearer picture of daylight performance since sDA contains no upper limit on illuminance levels and hence does not penalize direct sunlight/glare, while ASE provides the balance, thus helping architects make more balanced design decisions.

2030 Challenge

The current (year 2015) performance target of the 2030 Challenge requires all new buildings, developments and major renovations to be designed to meet a fossil fuel, GHG-emitting, energy consumption performance standard of 70% below the regional (or country) average/median for that building type. In the case of an office building in Minneapolis, the current target Energy Use Intensity (EUI) would be 27 kBTU/sf/yr based on the regional average.

SOFTWARE FUNDAMENTALS

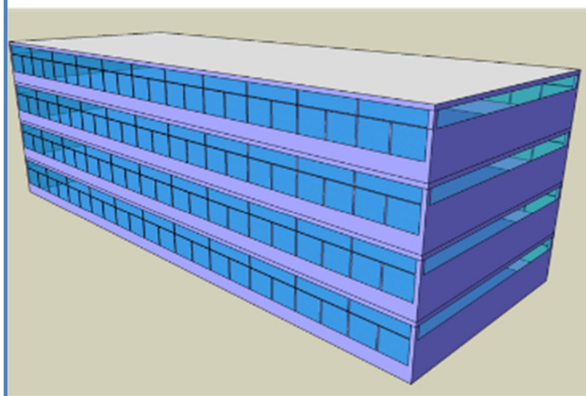
Out of the few software available for early stage design optimization is Sefaira Architecture. It has the capability to provide real-time feedback in SketchUp or Revit (the platforms that most architects use for 3D visualization in early stages of design) on both energy and daylight metrics and hence chosen to demonstrate the methodology described in the next section. One of the other software tools that can also suit this purpose is DIVA for Rhino, which takes a considerably longer time to produce more accurate results, but such accuracy might not be necessary for quick comparative studies in early design stages. It is worth noting here that the focus of this study is not on the potential of a particular software itself but rather on the applications of the methodology discussed in the later section to the architectural practice. Hence any software that could propagate the latter would be equally applicable.

Sefaira requires four main inputs – modeled geometry in SketchUp or Revit, occupancy type, location, and building properties that can be adjusted manually or based on common baselines like ASHRAE and Part L – to produce four main outputs – energy use intensity (EUI) compared against 2030 Challenge benckmark, energy segments (heating, cooling, lighting, appliances), percentage floor area with glare per the LEEDv4 ASE metric, and percentage of floor are that is well-lit per the LEEDv4 sDA metric. The Real Time Analysis Plug-in calculates energy use using Sefaira's Fulcrum engine which is based on ASHRAE's radiant time series method of calculation. Daylighting is calculated with Radiance (providing backwards ray-tracing), and DAYSIM (layering climate data onto the analysis). The biggest advantage of Sefaira is that it does not need the designers to leave their native CAD environment and change their design process while performing energy and daylight analysis, hence integrating the latter into the already existing work flow. More information on the functioning of the software can be found at http://sefaira.com/sefaira-architecture/.

METHODOLOGY

Base Case Shoebox Model

Before proceeding to demonstrate the methodology, a base case building has to be chosen upon which the parametric analysis has to be performed, since a design's context and brief sets some limits for the same. A simple four-story rectangular shoebox office building located in Minneapolis, Minnesota is chosen as the base case with properties as shown in Figure 2.



- Location – Minneapolis, MN
- Shape - Rectangular
- Aspect ratio – 2.67 (160'/60')
- Floor to ceiling height – 13'
- No. of stories – 4
- Orientation – 0 degrees (elongated on east-west axis)
- WWAR North – 65.4%
- WWAR South – 65.4%
- WWAR East – 23.1%
- WWAR West – 23.1%
- Sill height North – 3.5'
- Sill height South – 3.5'
- Sill height East – 9'
- Sill height West – 9'

Figure 2: Base case shoebox model

The envelope properties, and HVAC, lighting and appliance efficiencies are set to the ASHRAE 90.1-2013 baseline for climate zone 6 as available in the Sefaira for SketchUp Plugin (shown in Figure 3).

No surrounding buildings are considered for this demonstrative study for simplicity but context is certainly a very important aspect to determine optimum design parameters for real buildings.

<u>BASELINE: ASHRAE 90.1-2013 – Climate Zone 6</u>

- Wall Insulation - R-12.62
- Floor Insulation – R-19.58
- Roof Insulation – R-31.55
- Glazing U-Factor - 0.32
- VLT – 0.42
- SHGC – 0.4
- Heating Efficiency – 1.01 COP
- Cooling Efficiency – 3 COP
- Infiltration Rate – 0.39 cfm/sf
- Ventilation Rate – 0.06 cfm/sf
- Appliance – 0.75 W/sf
- Lighting – 0.82 W/sf

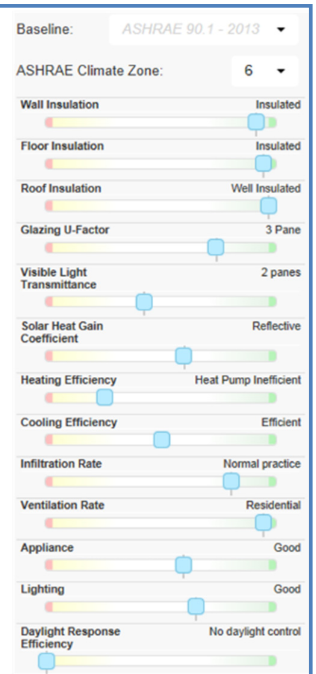


Figure 3: Envelope properties, and HVAC, lighting and appliance efficiencies

Parameters under Study

Since the broader goal of this study is to explore the interactions between energy and daylight performance and test the potential of a well day-lit building using just passive design strategies to achieve 2030 Challenge, the parameters chosen to be investigated in this study are passive design strategies that have an impact primarily on daylight performance, while their impact on energy performance is also studied. A range of values for each of these parameters is set based on a general understanding of an architect's design limits for the particular building type. Parametric analysis is performed within this range for each of the passive strategies to investigate their individual effect on energy and daylight performance. In all cases, building floor area is kept constant as architects usually work with a fixed space program. The parameters and their respective range of values are listed in Figure 4.

Parameter	Range
Aspect Ratio	1-6 (min. depth 40')
Floor to Ceiling Height	11'-15'
Number of Stories	2-9 (min. depth 40')
Orientation	0-180 degrees
Shading Projection - East	0-100%
Shading Projection - West	0-100%
Shading Projection - North	0-100%
Shading Projection - South	0-100%
WWAR - East	0-90%
WWAR - West	0-90%
WWAR - North	10-90%
WWAR - South	10-90%
Sill Height - East	3'-9'
Sill Height - West	3'-9'
Sill Height - North	0.5'-3.5'
Sill Height - South	0.5'-3.5'

Figure 4: Parameters and respective ranges

Step 1: Individual Parametric Analysis

To understand the sensitivity of each parameter in terms of changes in energy use and daylight availability, the base case model is analyzed individually for each parameter over its respective range of values (maintaining all other parameters the same as the base case) to determine the percentage change in energy use, percentage of well-lit floor area (based on sDA) and percentage of floor area under glare (based on ASE) from the worst to the best case. This step helps the architects understand which parameter change has the highest potential to impact performance and must definitely be considered while making any design changes to avoid resulting in a worst performing case, and which ones do not matter much and hence can be left to aesthetic creativity in the later stages of the design. In addition, it lets the architects check the results against their usual rules of thumb and question them if they differ from each other. This step can also be used by itself if a particular design change is being investigated separately instead of optimizing the design holistically.

Step 2: Prioritization of Parameters

Following Step 1, the parameters are then arranged in the decreasing order of priority based on their sensitivity to changes in percentage of well-lit floor area by determining the percentage improvement of the best case over the worst case within the range of values for each parameter. For example, for aspect ratio parameter as shown in the results section (Figure 5), the best case is 49% well-lit floor area (aspect ratio 2) and the worst case is 29% (aspect ratio 6), so the percentage improvement of the best case over the worst case is (49%-29%)/29% = 69% (Figure 21).

Step 3: Base Case Optimization

Once the parameters are prioritized, the base case model is then optimized in that order of parameters for the maximum percentage of well-lit floor area, each time building on the best case of the previous parameter optimization. The percentage of floor area under glare is also kept under check at each step to make sure that it doesn't increase over the best case of the previous step.

Step 4: Final Output Analysis

The last step is to analyze the improvement in the final outputs (percentage of well-lit floor area, percentage of floor area under glare, and EUI) of the ultimate best case over the base case. This step also involves exploring the possibility of using daylight controls to reap the benefits of adequate daylight to decrease energy use thereby achieving the 2030 Challenge. Finally, the best case shoebox model is compared against the base case in terms of the actual daylight distribution on the floor plates, the depth of daylight penetration into the floor plate, and under-lit areas of the plan to determine basic zoning of spaces.

RESULTS AND DISCUSSION

Step 1: Individual Parametric Analysis

PARAMETER 1: ***Aspect Ratio***

Result: Daylighting is optimized with a maximum percentage of well-lit floor area at aspect ratio 2 after which the percentage of floor area under glare takes over resulting in a decreasing percentage of well-lit floor area. EUI increases with increasing aspect ratio.

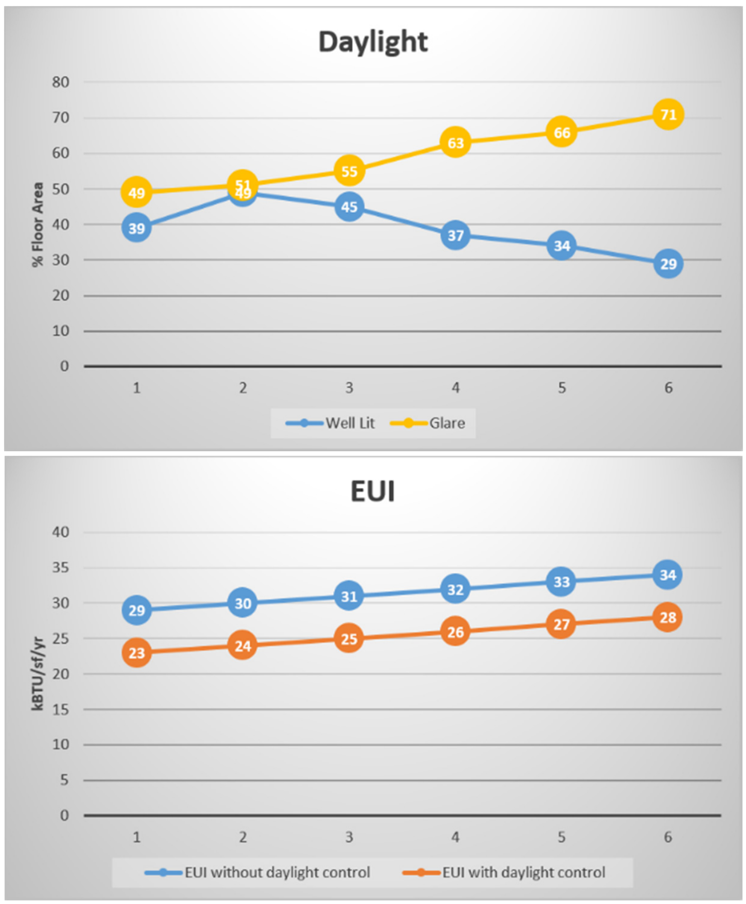


Figure 5: Aspect Ratio Parametric Analysis

Explanation: For cold climates, energy use is directly proportional to exposed surface area of the building as heat loss through the enclosure dominates the annual energy use. Since an aspect ratio of 1 (square-shaped building) has the lowest surface area (only next to circular-shape), it also has the lowest EUI. The depth of daylight penetration remains the same for a particular window head height and hence daylight does not penetrate far enough in deeper buildings. But as the building gets thinner (increasing aspect ratio), daylight penetrates from either sides of the building gradually covering the entire floor area and exceeds the well-lit limit (1000 lux) after a certain point causing glare.

PARAMETER 2: ***Floor to Ceiling Height***

Result: As the floor to ceiling height increases, percentage of well-lit floor area decreases with an increase in floor area under glare. The EUI increases with an increasing floor height.

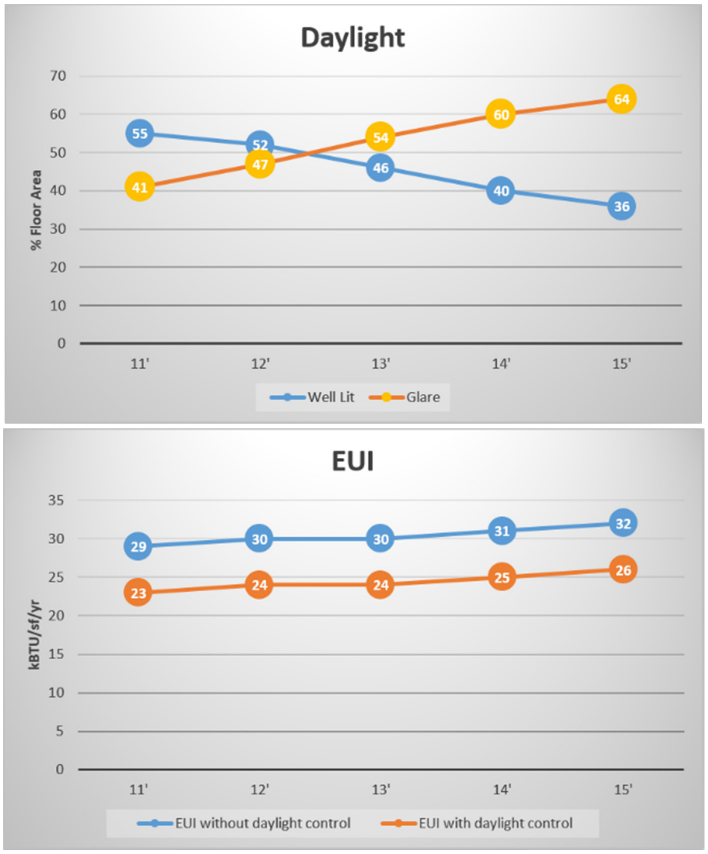
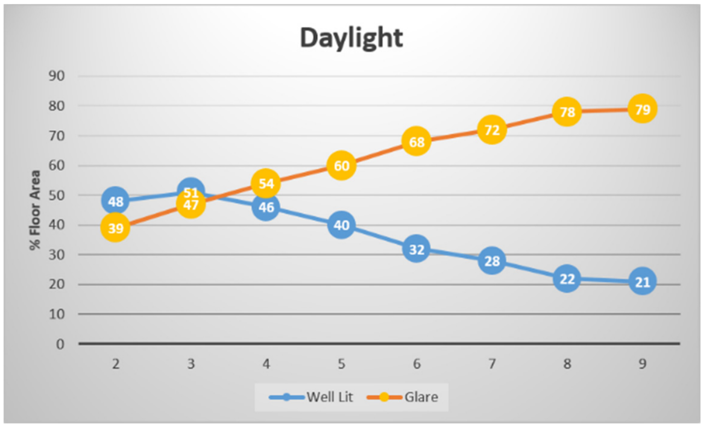


Figure 6: Floor to Ceiling Height Parametric Analysis

Explanation: An increase in floor height increases the volume of the space that needs to be conditioned and also increases the wall and window area (WWAR remains constant) resulting in greater heat loss and hence higher EUI. As the floor to ceiling height increases, the head height of the windows also increases, resulting in deeper daylight penetration and higher glare.

*PARAMETER 3: **Number of Stories***

Result: In this case, the aspect ratio is kept constant with an increasing number of stories. Percentage of well-lit floor area peaks at 3 stories and then drops down while the percentage of floor area under glare increases with increasing number of stories. The EUI increases at a slow pace as the number of stories increases.



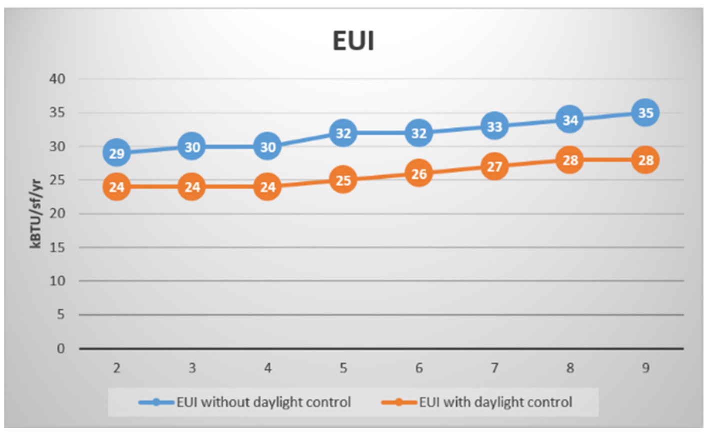


Figure 7: Number of Stories Parametric Analysis

Explanation: Since the aspect ratio is kept constant, the depth of the building decreases with increasing number of stories. The explanation on the depth of daylight penetration is the same as that for aspect ratio parameter and so is that for EUI where the surface area of the enclosure increases with increasing stories thereby increasing the EUI.

PARAMETER 4: ***Orientation***

Result: Percentage of well-lit floor area peaks and the percentage of floor area under glare is the least when the building's transverse axis is orientated 22.5 degrees east of south, and the vice-versa is true when it is oriented at 90 degrees. The energy use does not vary much with a change in building orientation.

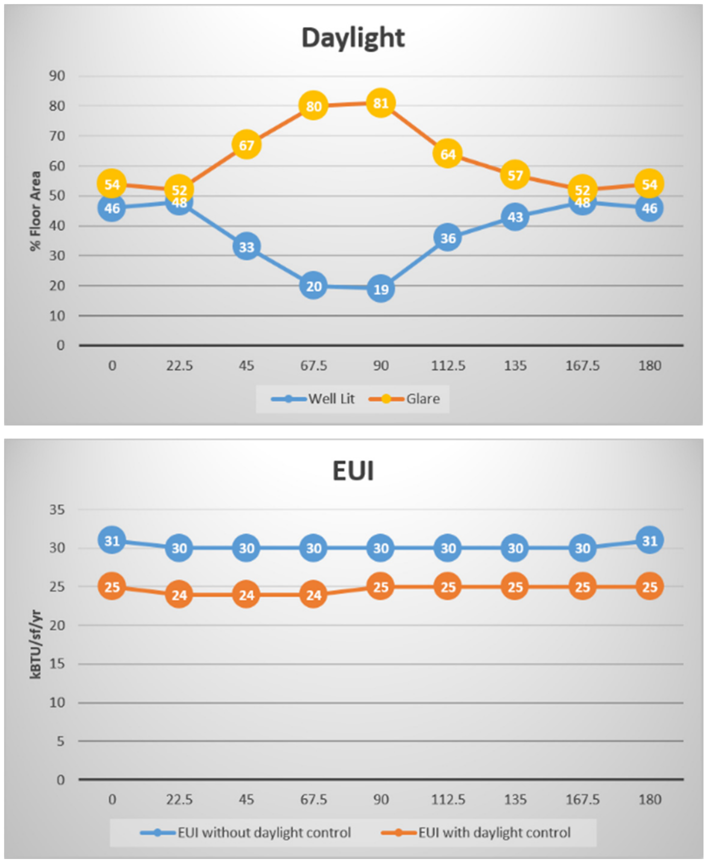


Figure 8: Orientation Parametric Analysis

Explanation: The energy use of buildings in cold climates is dominated by heating loads as a result of heat losses through the envelope during winter. This heat loss is a function of exposed surface area of the building and does not depend much on the orientation of the building, and hence the EUI remains fairly constant. The cooling load might vary slightly owing to some self-shading effects resulting in the slight variations in EUI. Daylight potential is maximum in south orientation since the sun culminates in the south (in northern hemispheres) also resulting in glare unless appropriate shading devices are in place. The east and west orientations of the building cause glare due to the low angles of the sun in the morning and evening respectively. The north orientation works well for indirect daylight without glare potential. Hence a building with its longer side oriented along the east-west axis is expected to have the highest percentage of well-lit floor area (as expected with a rule of thumb). The difference in the results might be explained by considering the self-shading effects of the building.

PARAMETER 5: ***Vertical Shading Projection – East***

Result: Percentage of well-lit floor area increases and percentage of floor area under glare decreases with increasing vertical shading depth on the east face of the building. There is no change in EUI.

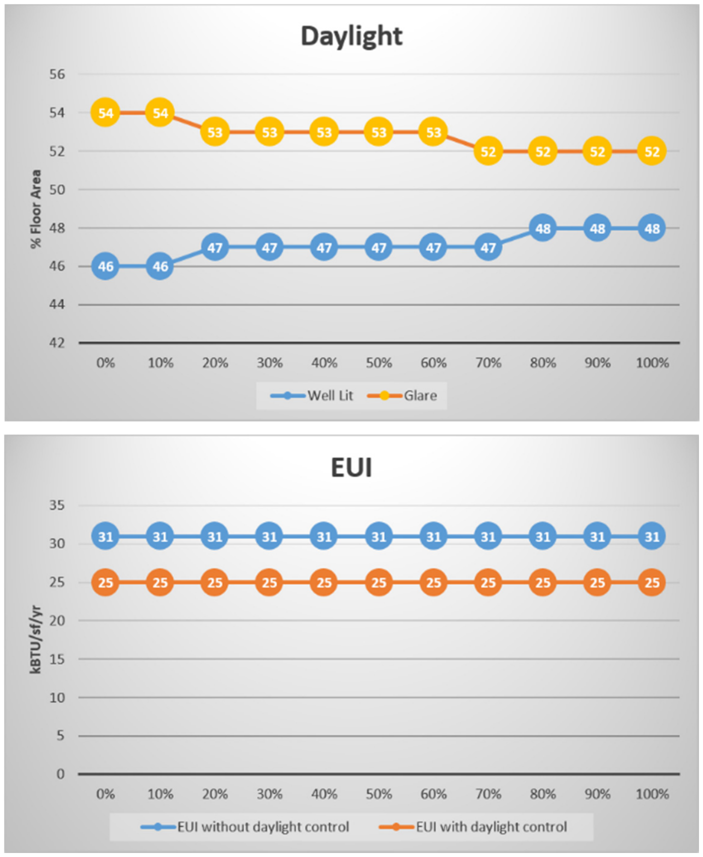


Figure 9: East Shading Parametric Analysis

Explanation: Vertical shading on the east reduces the glare caused by low angles of the sun in the early hours of the day, and thereby increases the well-lit floor area. The EUI is driven mostly by heating load due to heat losses through the exterior enclosure which is not affected by shading, and hence remains nearly constant.

PARAMETER 6: ***Vertical Shading Projection – West***

Result: Percentage of well-lit floor area increases and percentage of floor area under glare decreases with increasing vertical shading depth on the west face of the building until a certain point (vertical shading depth of 60% the window width) after which both remain constant.

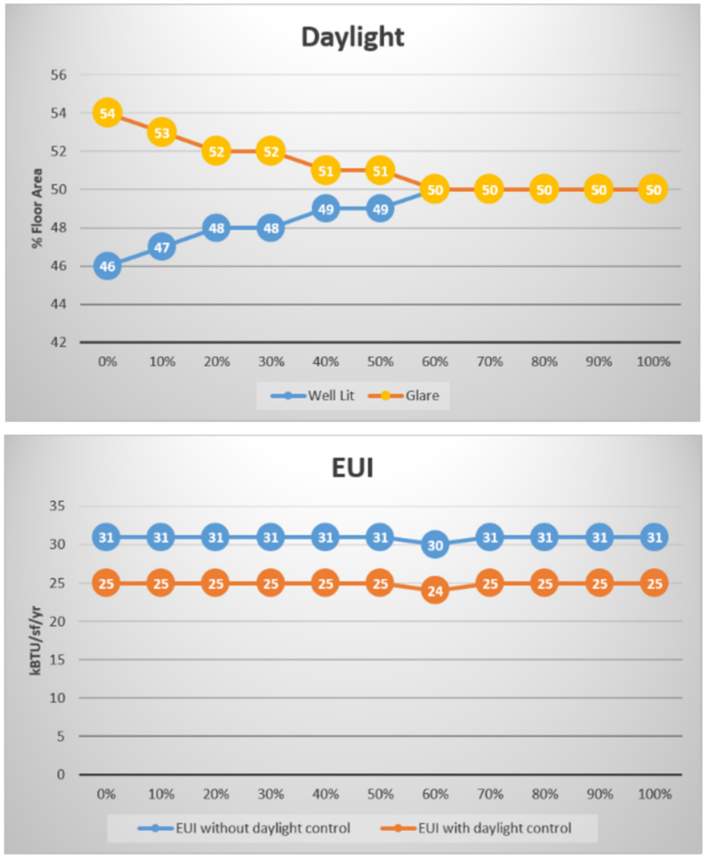


Figure 10: West Shading Parametric Analysis

Explanation: A greater percentage of occupied hours in a typical office fall in the late afternoon when the sun is in the west than in the early morning when the sun is in the east. Hence west-glazing poses a higher risk of glare (greater than 1000 lux of daylight for more than 250 occupied hours per year as per the definition of ASE) than east glazing, hence making the west shading less effective in mitigating glare after a certain point when compared to east shading. The EUI remains nearly constant for the same reason as that for east shading.

PARAMETER 7: ***Horizontal Shading Projection – North***

Result: North shading neither affects the percentage well-lit floor area and floor area under glare nor the EUI.

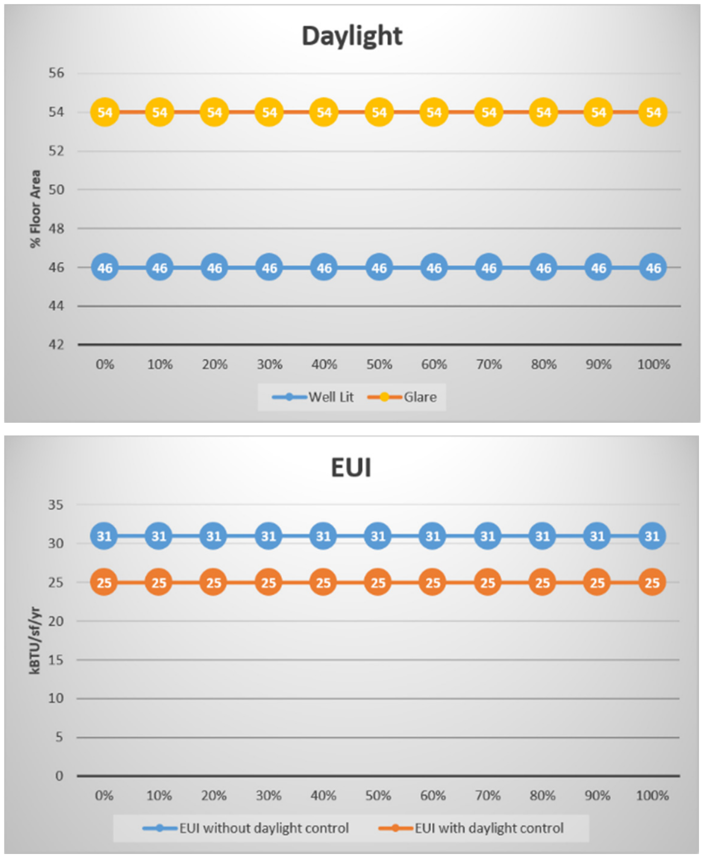


Figure 11: North Shading Parametric Analysis

Explanation: The sun path is inclined towards the south, hence north glazing only sees indirect daylight that doesn't cause glare. So shading on the north does not serve any purpose in terms of daylight. The EUI is not affected as the heating loads are not affected by shading and the cooling loads are not affected either as the north does not see any direct sunlight.

PARAMETER 8: ***Horizontal Shading Projection – South***

Result: Horizontal shading on the south increases the well-lit floor area and decreases the floor area under glare. The EUI decreases with increasing shading on the south.

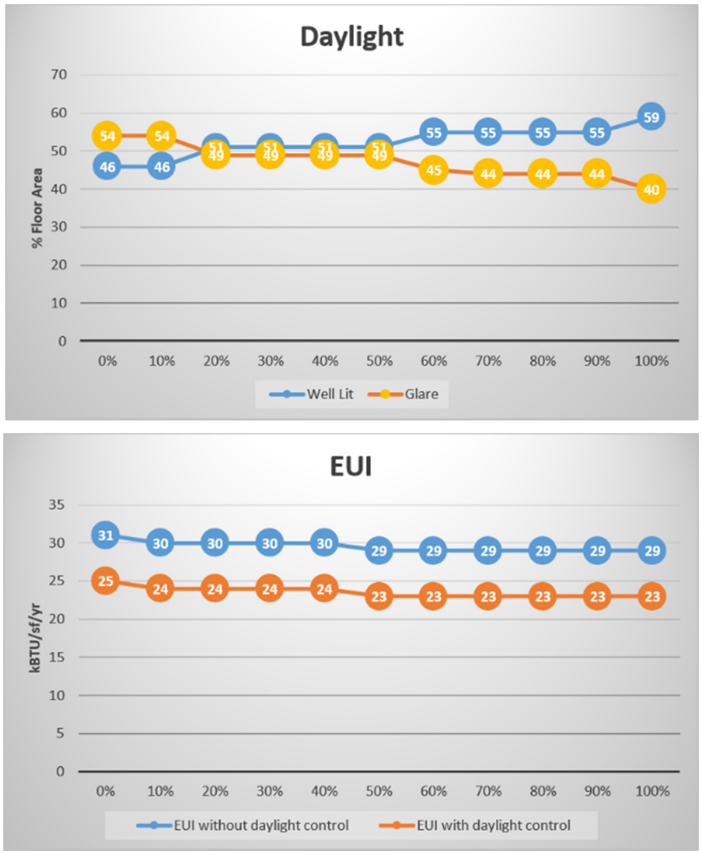


Figure 12: South Shading Parametric Analysis

Explanation: The south face of the building sees the maximum amount of direct sun as the sun path is inclined towards the south hence resulting in maximum glare potential. As a result, south shading is very effective in mitigating glare and increasing the well-lit floor area. Direct sunlight on the south for long hours during the day results in significantly higher cooling loads. Shading on the south blocks the direct sunlight thereby reducing the annual energy use gradually.

PARAMETER 9: ***Window to Wall Area Ratio (WWAR) – East***

Result: Percentage of well-lit floor area decreases and percentage of floor area under glare increases until a certain point (30% WWAR) after which both remain constant. The EUI increases gradually with increasing WWAR.

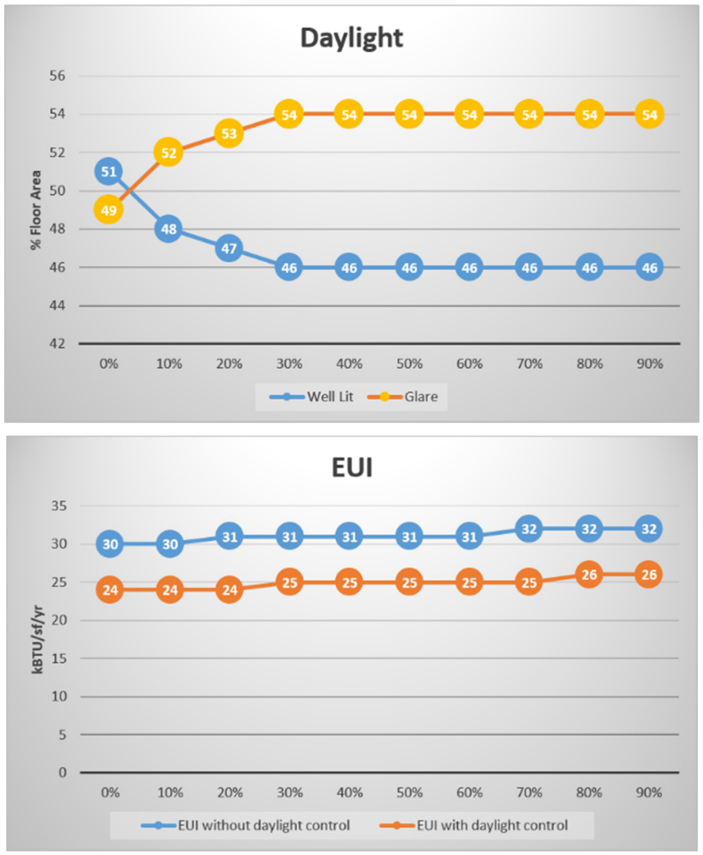


Figure 13: East WWAR Parametric Analysis

Explanation: More glazing results in more heat loss in the winter increasing the heating load. It also results in more solar gain which reduces the heating load in winter and increases cooling load in summer. Since heat losses dominate in winter in cold climates over solar gains (which are more prevalent in south orientation than east or west orientations), the net result of increasing the WWAR would be an increase in both heating and cooling loads. Since the head height remains constant while increasing the WWAR, the depth of daylight penetration remains the same but the glare dominates in east and west orientations due to low sun angles. Useful daylight is admitted through the part of the glazing higher in the wall (eg. clerestory windows) contributing to the well-lit floor area while the part of the glazing placed at view range of the user usually contributes to glare due to direct sun. In addition, the glazing below the desk height is neither useful for daylight nor for view. This could explain why the well-lit floor area and floor area under glare remain constant after reaching a certain WWAR.

PARAMETER 10: ***Window to Wall Area Ratio (WWAR) – West***

Result: Percentage of well-lit floor area decreases and percentage of floor area under glare increases until a certain point (30% WWAR) after which both remain constant. The EUI increases gradually with increasing WWAR.

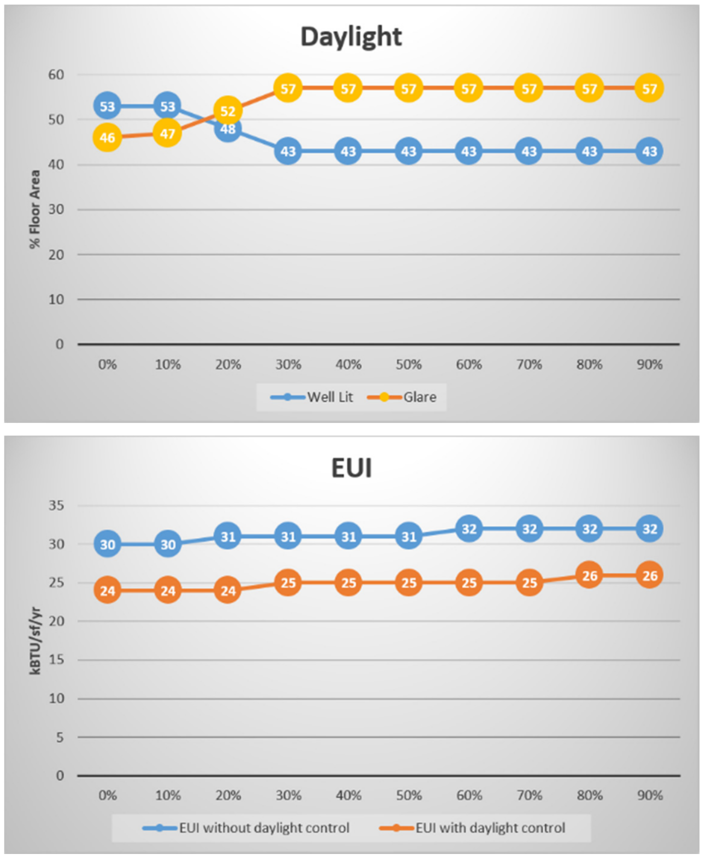


Figure 14: West WWAR Parametric Analysis

Explanation: The explanation of the results is similar to that for WWAR on the east orientation. The percentage of floor area under glare is more for the west exposure than the east as more occupied hours in an office fall late in the afternoon when the sun is in the west than in the early morning when the sun is in the east.

PARAMETER 11: ***Window to Wall Area Ratio (WWAR) – North***

Result: The percentage of floor area under glare is not affected by the north glazing but the percentage of well-lit floor area increases until a certain point (50% WWAR) and then remains constant. The EUI increases with increasing WWAR.

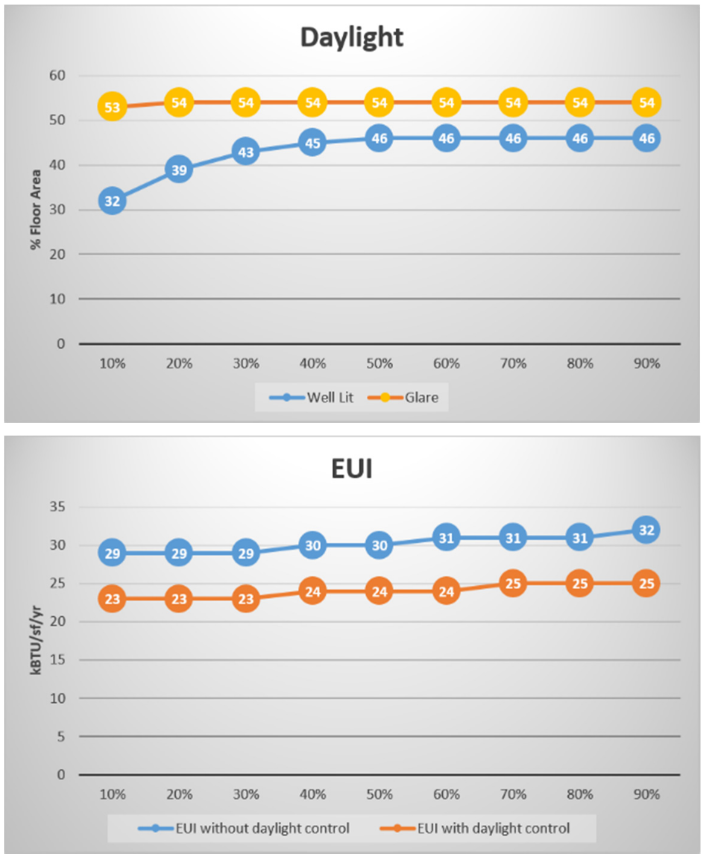
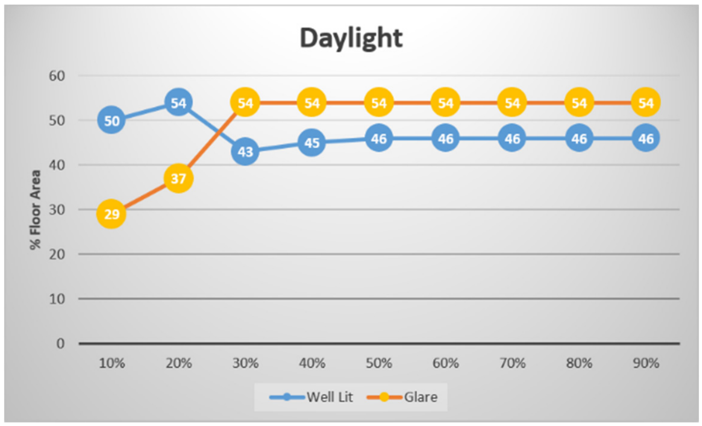


Figure 15: North WWAR Parametric Analysis

Explanation: More glazing results in more heat loss during the winter resulting in higher heating loads. Solar heat gain does not occur through the north glazing as the sun path is inclined towards the south in the northern hemisphere, hence it is neither penalized during the summer not benefitted during the winter. Since heating loads dominate the annual energy use in cold climates, the overall EUI increases with increasing WWAR on the north. North glazing is not affected by glare since there is no direct daylight through it, but that also results in under-lit spaces due to inadequate daylight. Hence the percentage of well-lit floor area increases with increasing WWAR on the north. But the amount of glazing below the desk height does not contribute to useful daylight thereby rendering higher WWARs useless in improving the well-lit floor area further.

PARAMETER 12: ***Window to Wall Area Ratio (WWAR) – South***

Result: Percentage of well-lit floor area peaks at 20% WWAR on the south and then drops down to remain constant after 50% WWAR along with the percentage of floor area under glare. EUI increases with increasing WWAR.



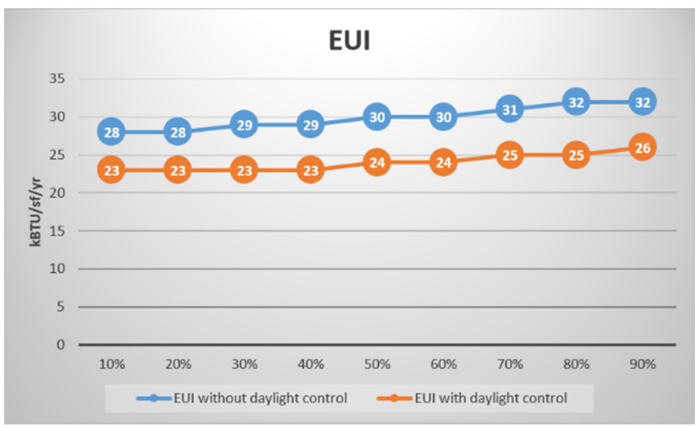
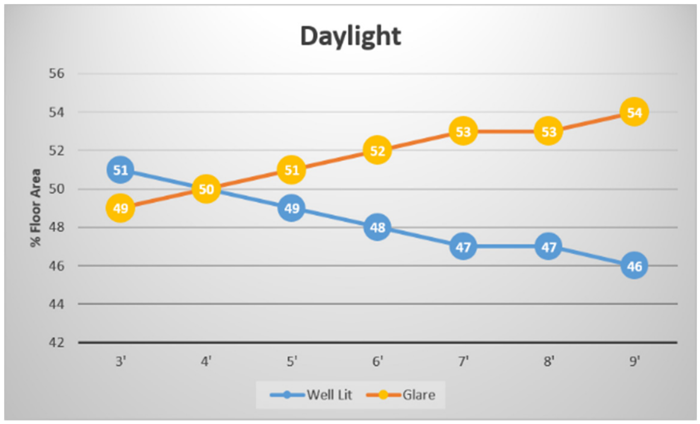


Figure 16: South WWAR Parametric Analysis

Explanation: The heating load increases with increasing WWAR due to greater heat losses. More glazing also results in more solar gain resulting in higher cooling loads during the summer and lower heating loads in the winter. Since heat losses dominate during the winter in cold climates, the overall annual energy use increases with increasing WWAR. South glazing is important for good daylight as the sun is oriented to the south most of the day, due to which low WWAR on the south results in under-lit spaces. Useful daylight is admitted through the part of the glazing higher in the wall (eg. clerestory windows) contributing to the well-lit floor area while the part of the glazing placed at view range of the user usually contributes to glare due to direct sun. In addition, the glazing below the desk height is neither useful for daylight nor for view. This could explain why the well-lit floor area peaks at a certain WWAR and then drops down to remain constant.

PARAMETER 13: ***Window Sill Height – East***

Result: Percentage of well-lit floor area decreases and percentage of floor area under glare increases with increasing sill height (at a constant WWAR). The EUI is not affected by the placement of the window in the wall.



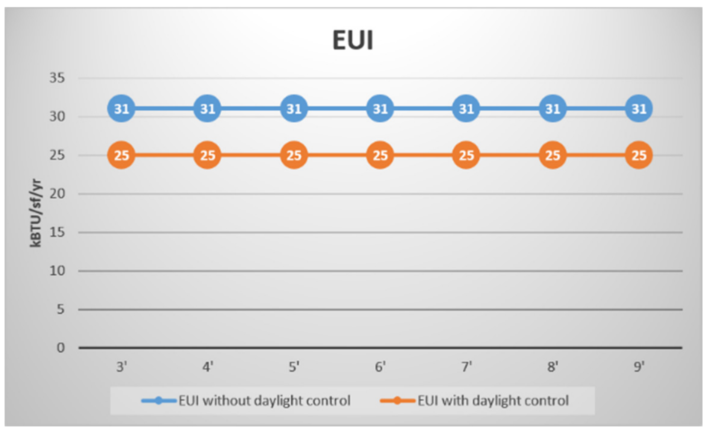
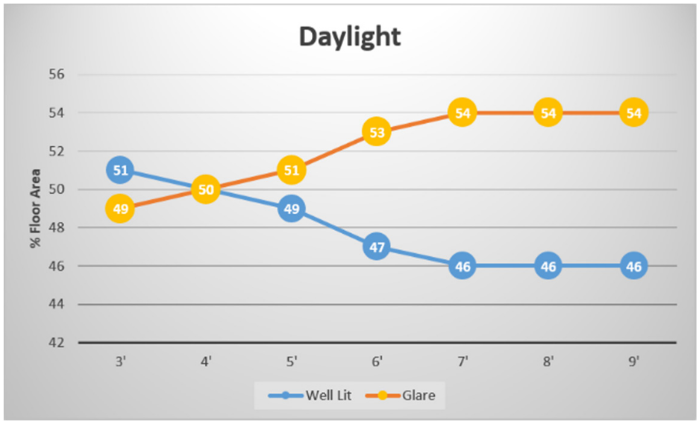


Figure 17: East Window Sill Height Parametric Analysis

Explanation: The heat gain and losses through glazing are determined by the amount of glazing and not by its location in the wall, hence the EUI remains unaffected. The head height determines how deep the daylight penetrates into the space. Since direct light causes glare, the deeper the direct light penetrates, the higher is the glare potential thereby reducing the well-lit floor area. Therefore greater head height could lead to higher glare and lower well-lit space.

PARAMETER 14: ***Window Sill Height – West***

Result: Percentage of well-lit floor area decreases and percentage of floor area under glare increases with increasing sill height (at a constant WWAR). The EUI is not affected by the placement of the window in the wall.



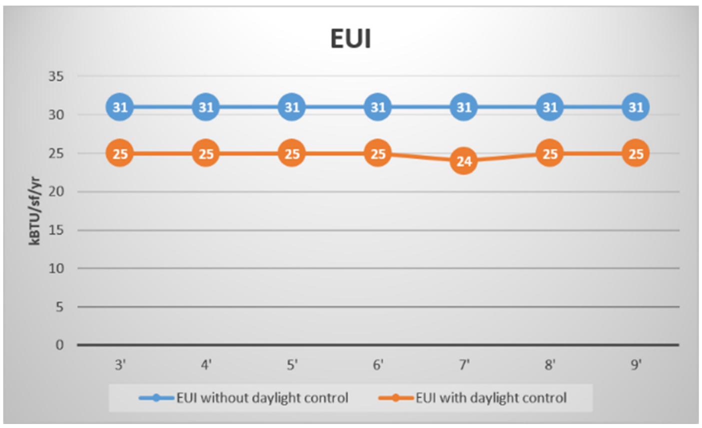


Figure 18: West Window Sill Height Parametric Analysis

Explanation: The explanation of the results is similar to that of the window sill height on the east face of the building.

PARAMETER 15: ***Window Sill Height – North***

Result: Percentage of well-lit floor area and floor area under glare, and EUI remain unaffected by the placement of the window in the wall (at a constant WWAR)

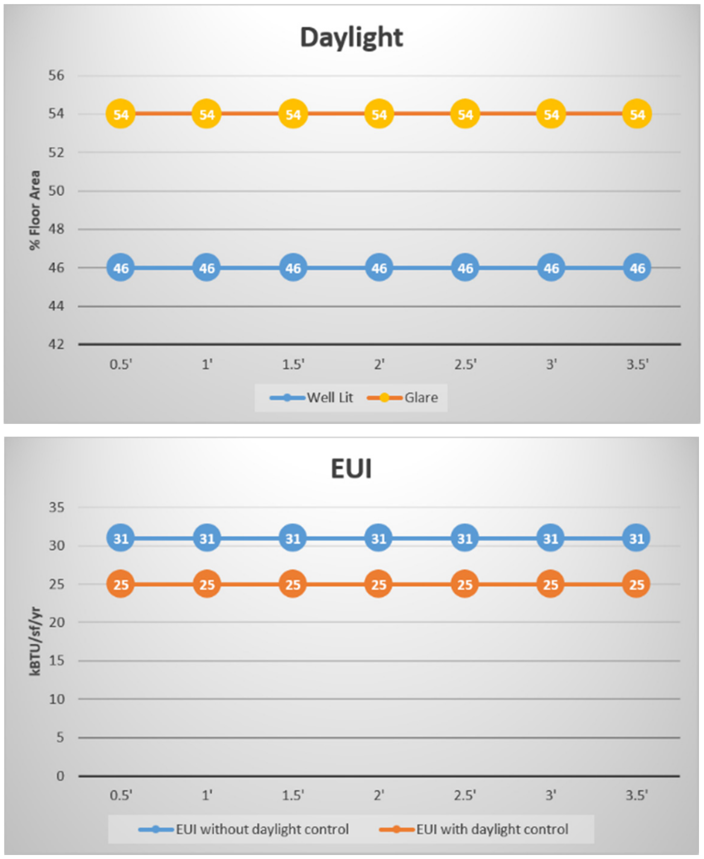
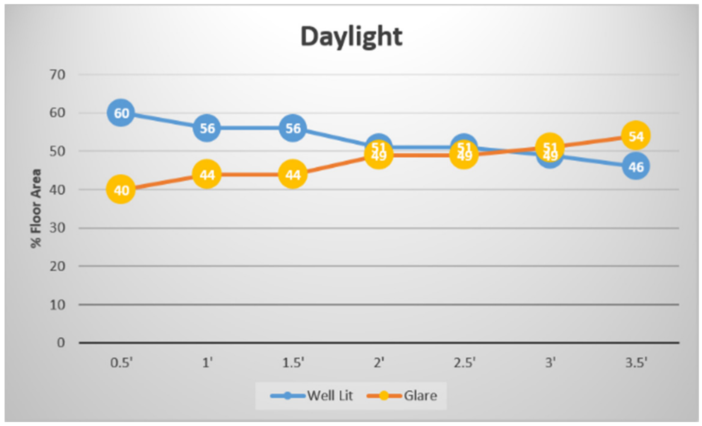


Figure 19: North Window Sill Height Parametric Analysis

Explanation: The heat gain and losses through glazing are determined by the amount of glazing and not by its location in the wall, hence the EUI remains unaffected. The North glazing only receives indirect light and is not exposed to direct light. Hence the placement of the window in the wall does not affect the well-lit floor area or the floor area under glare as long as the WWAR remains constant.

PARAMETER 16: ***Window Sill Height – South***

Result: Percentage of well-lit floor area decreases and percentage of floor area under glare increases with increasing sill height (at a constant WWAR). The EUI is not affected by the placement of the window in the wall.



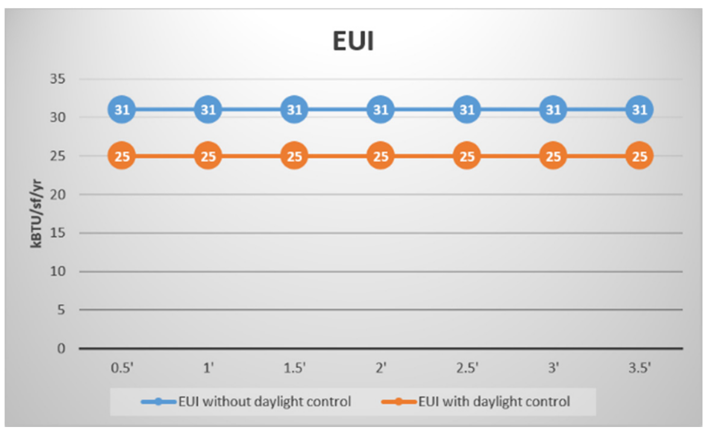


Figure 20: South Window Sill Height Parametric Analysis

Explanation: The explanation of the results is similar to that of the window sill height on the east and west faces of the building. The glare caused by deeper penetration of direct light can be mitigated by using appropriate exterior and interior shading devices (which is more difficult on the east and west orientations than the south due to lower sun angles).

Step 2: Prioritization of Parameters

The bar chart below shows the percentage improvement in well-lit floor area, floor area under glare and EUI of the best case over the worst case in each parameter range arranged in the decreasing order of percentage improvement in well-lit floor area. Orientation and number of stories are the biggest players affecting the amount of well-lit space followed by aspect ratio, floor to ceiling height and WWAR-North.

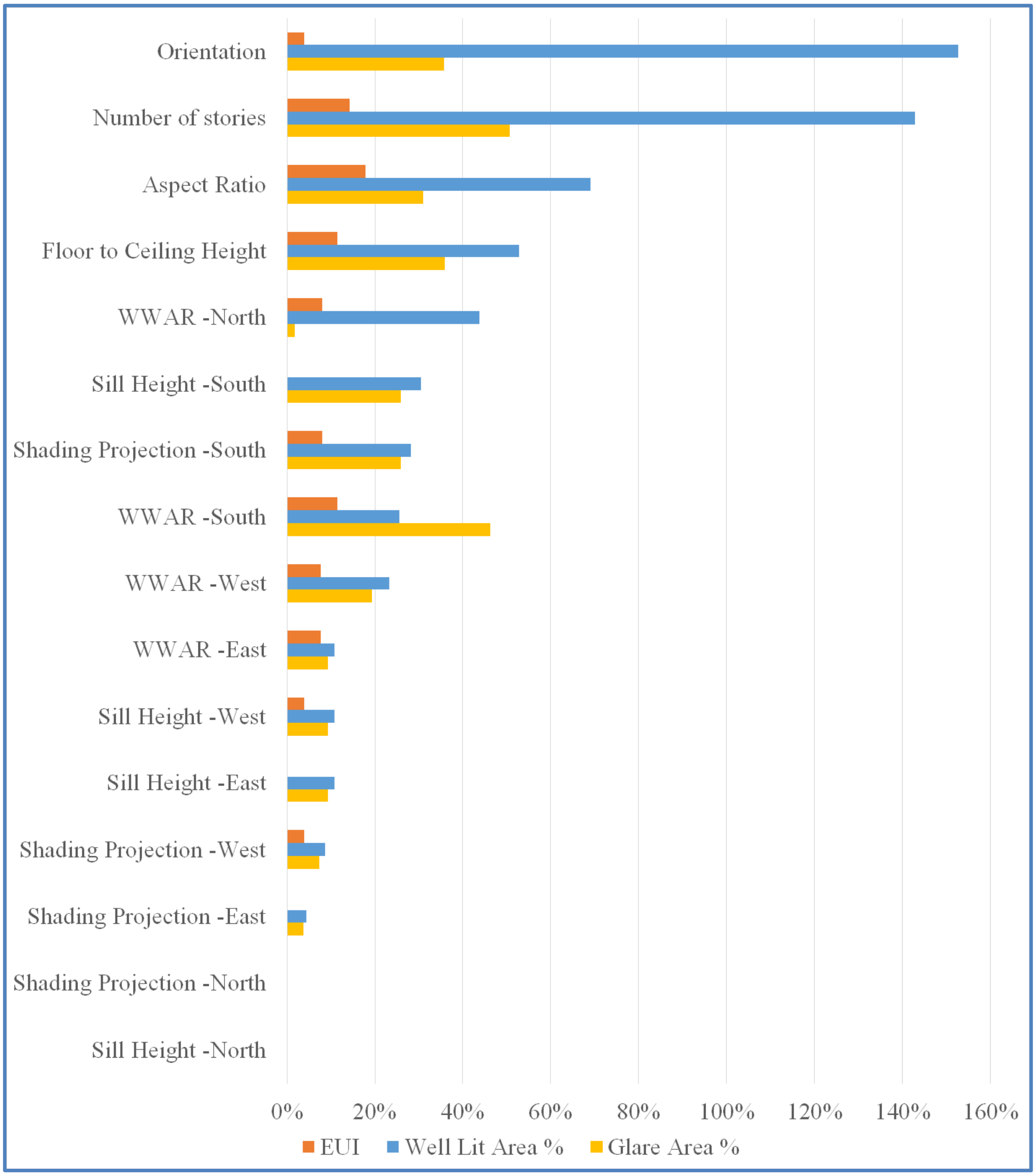
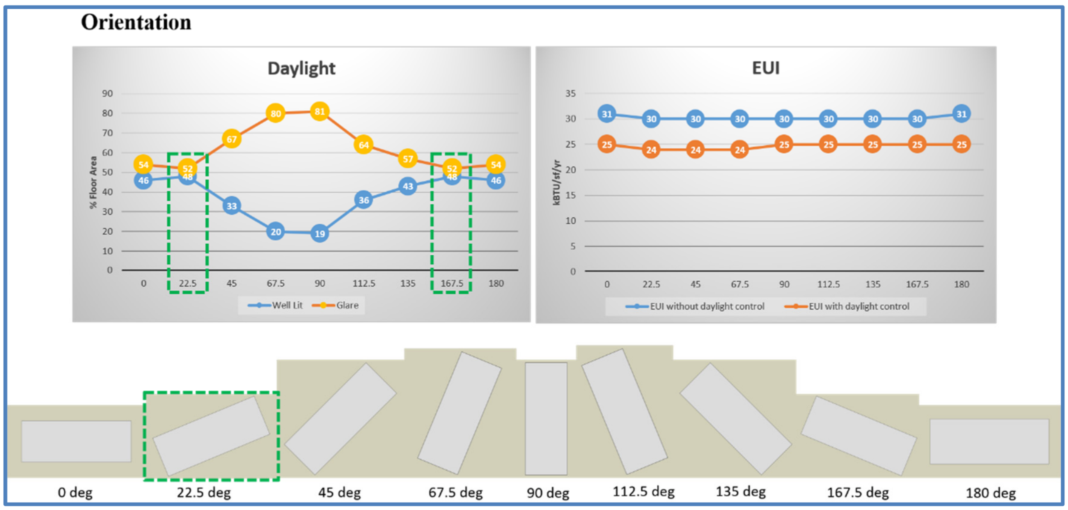
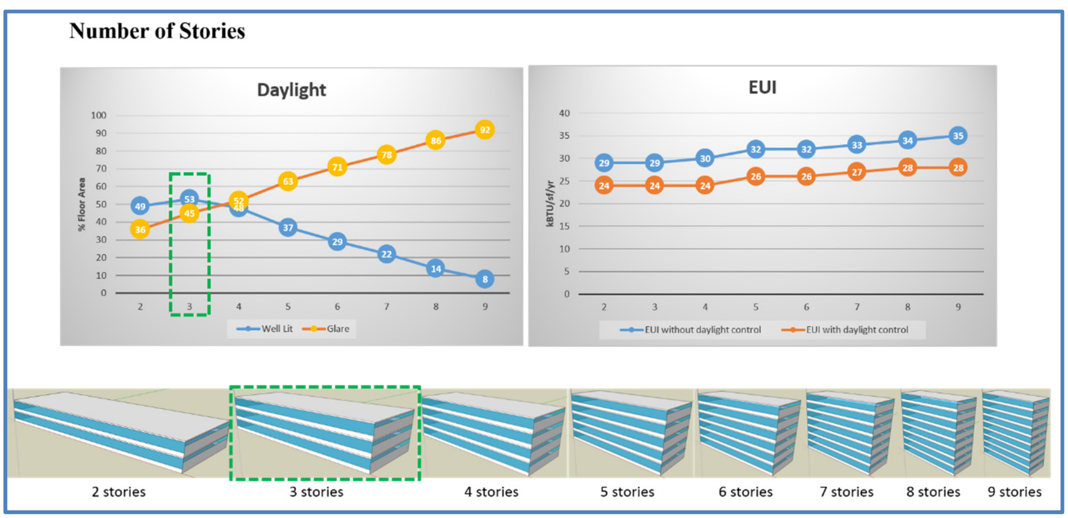


Figure 21: Decreasing Rank Order of Well-Lit Area % Improvement

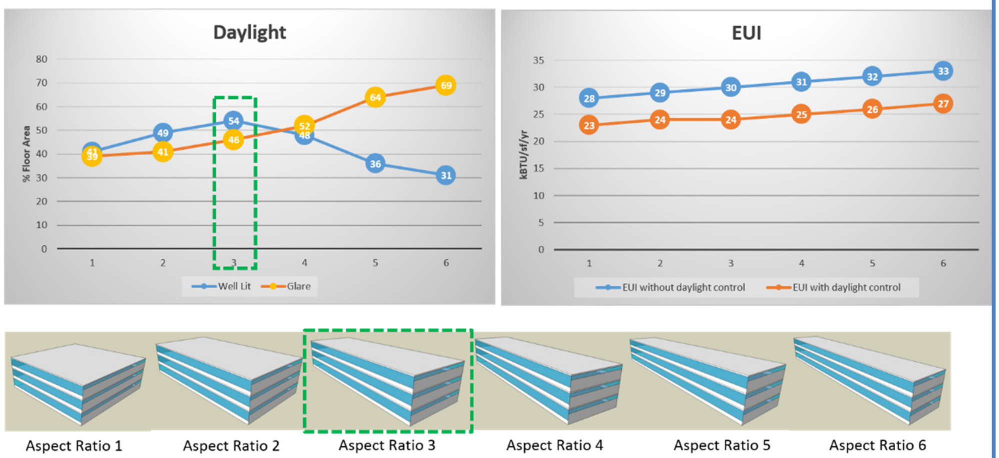
Step 3: Base Case Optimization

The base case is optimized in the order of parameters determined in Step 2 as shown in the set of graphs below. In each parameter range, the option with maximum well-lit floor area is chosen to proceed to the next parameter optimization, while making sure that the floor area under glare does not exceed that of the previous optimization (in fact the graphs show that it reduces at each optimization step). It can also be noted that the EUI does not vary much over the course of the optimization.

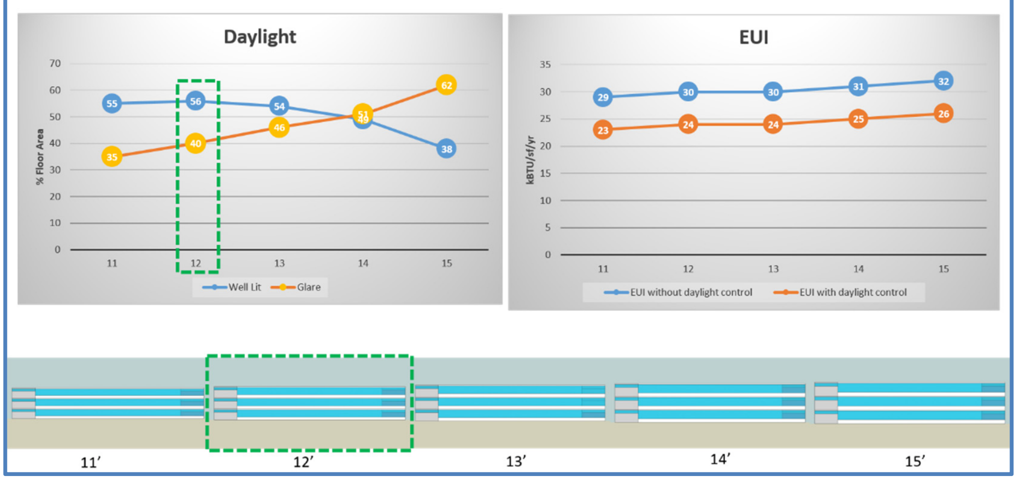




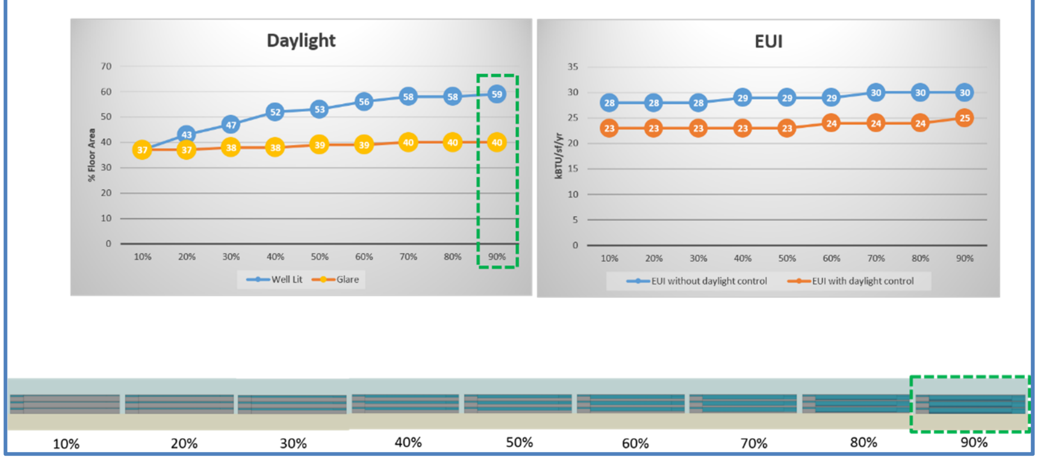
Aspect Ratio



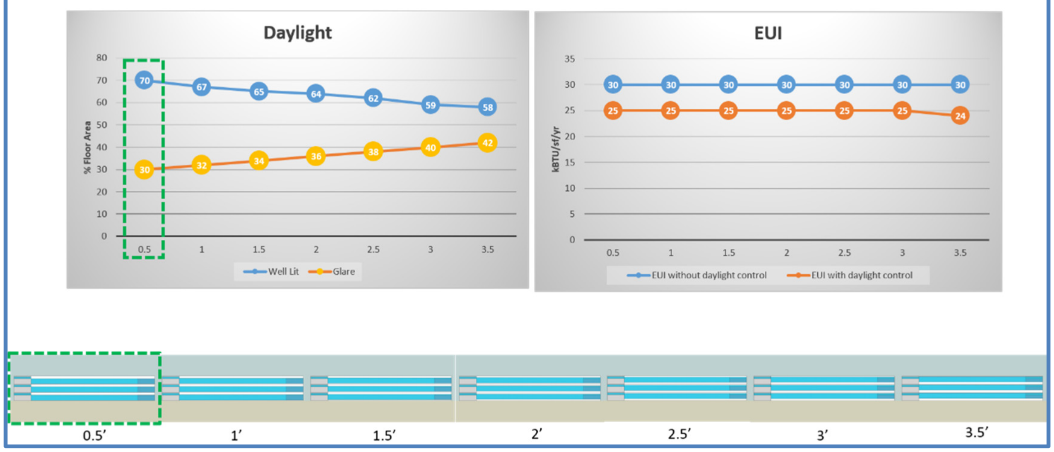
Floor to Ceiling Height



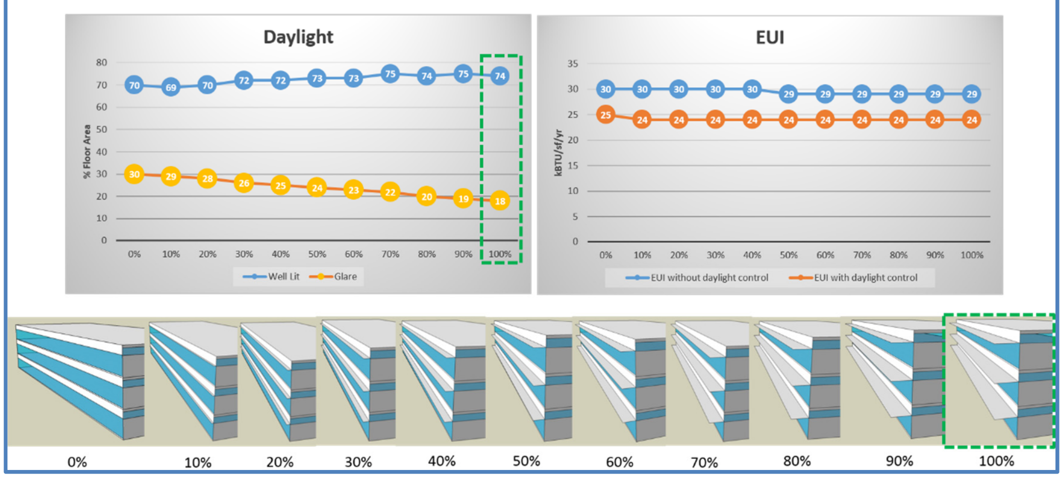
WWAR - North



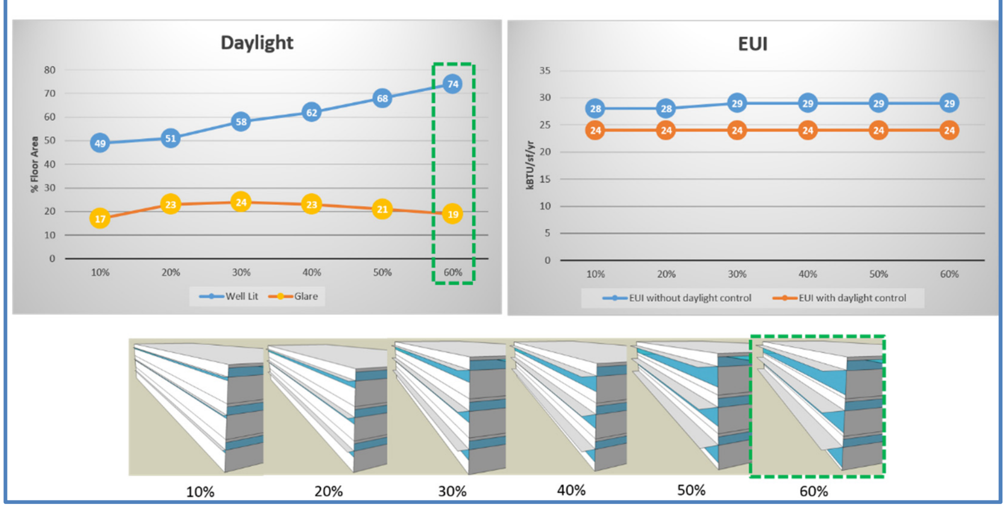
Sill Height - South



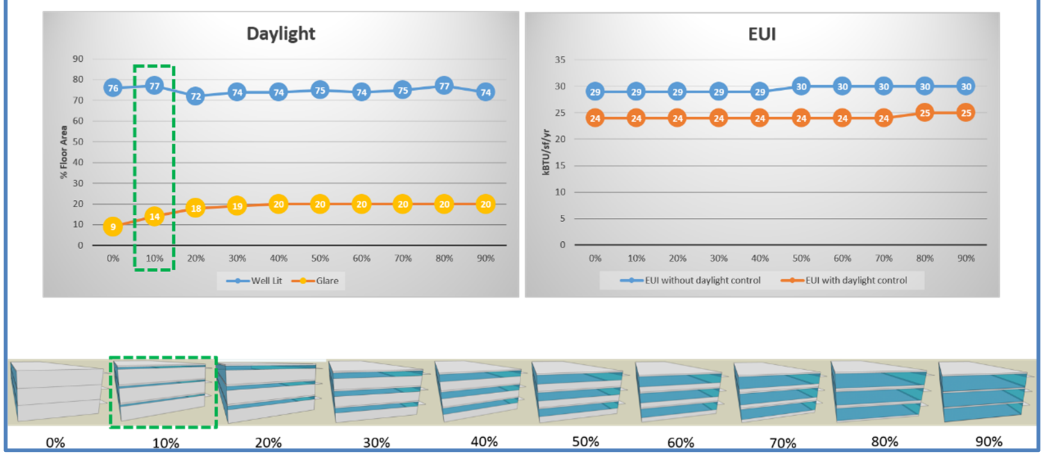
Shading Projection - South



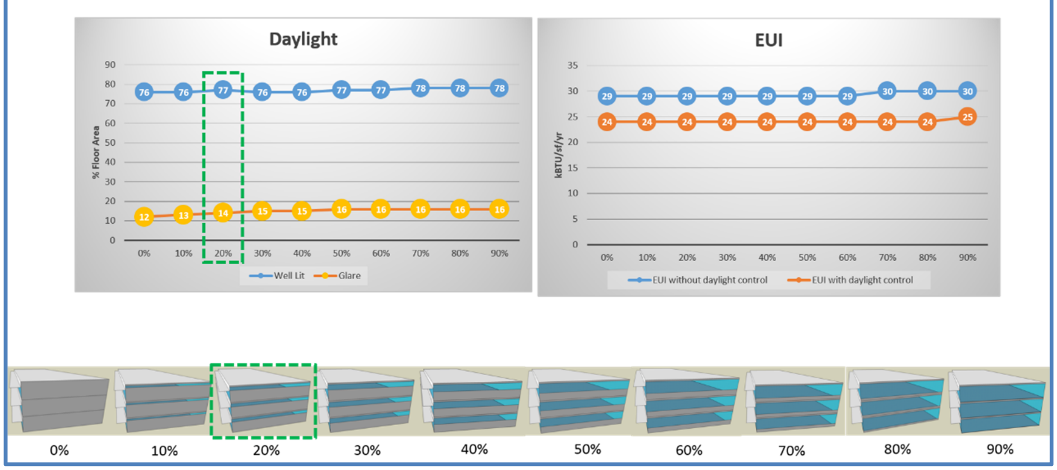
WWAR - South



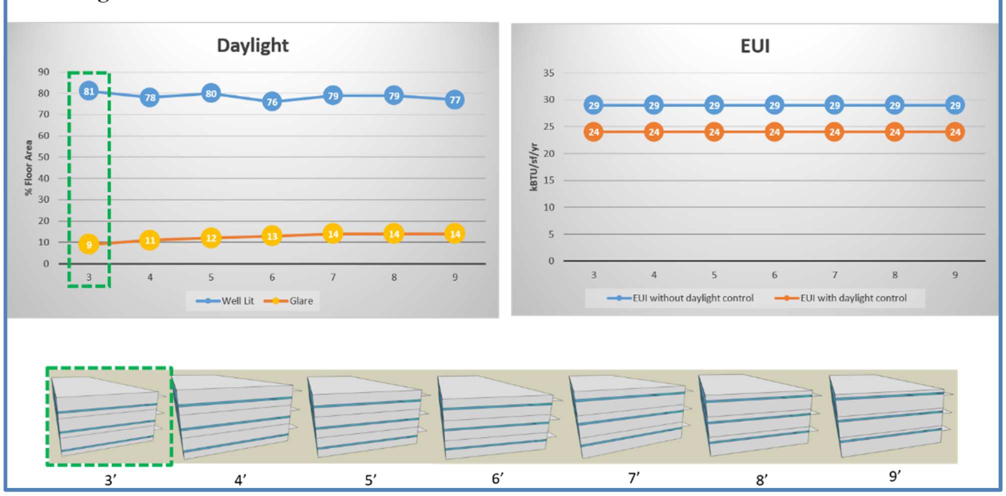
WWAR - West



WWAR - East



Sill Height - West



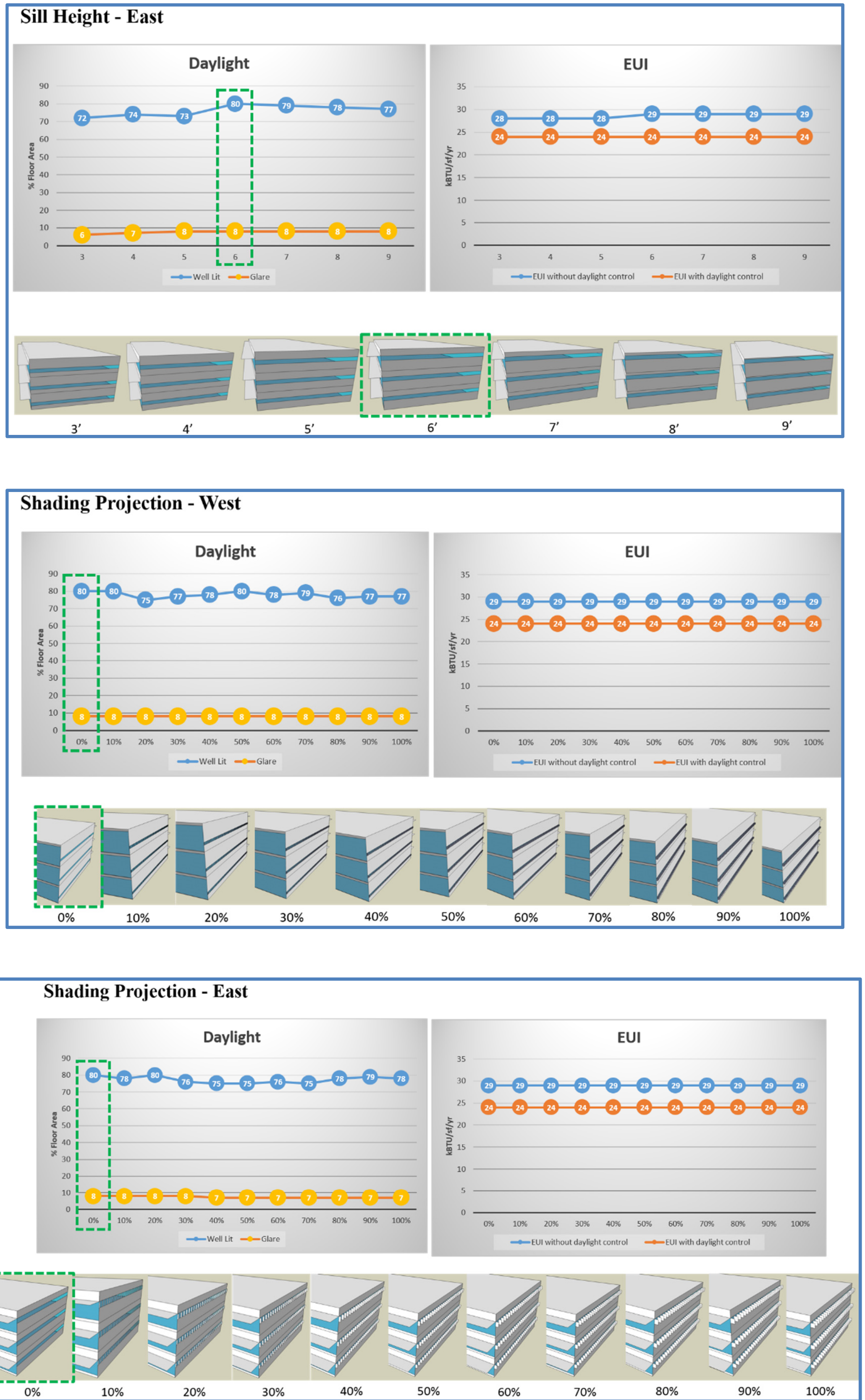


Figure 22: Series of Base Case Optimization Graphs

The optimized parameters in comparison to the original base case parameters are shown in the following table. The architect can choose to end the optimization process at any intermediate step based on the intended degree of optimization as long as the most effective parameters are optimized.

Step 4: Final Output Analysis

The bar chart below shows the progressive improvement of the well-lit floor area (46% to 80%) and the area under glare (54% to 8%) over the course of the optimization.

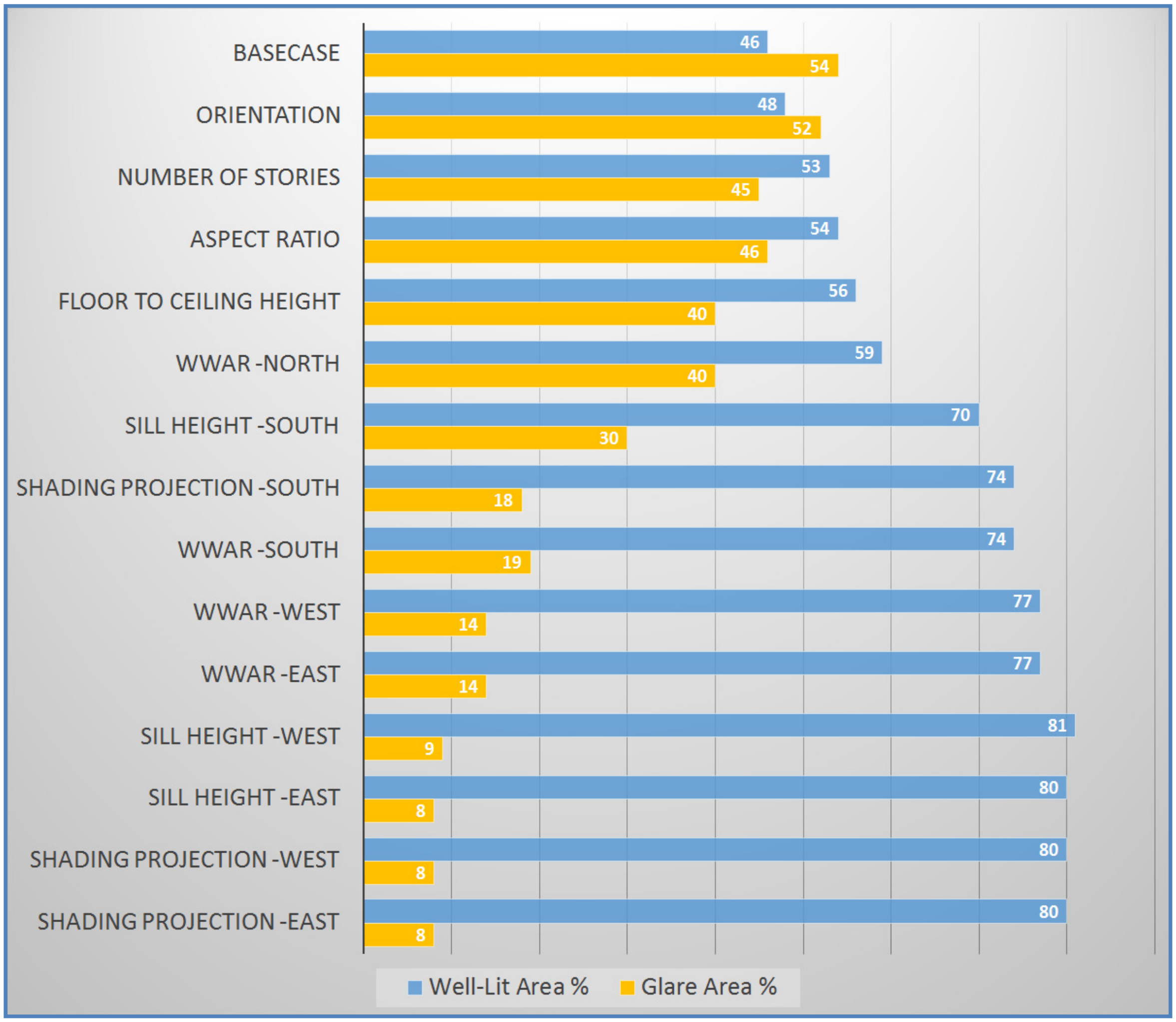
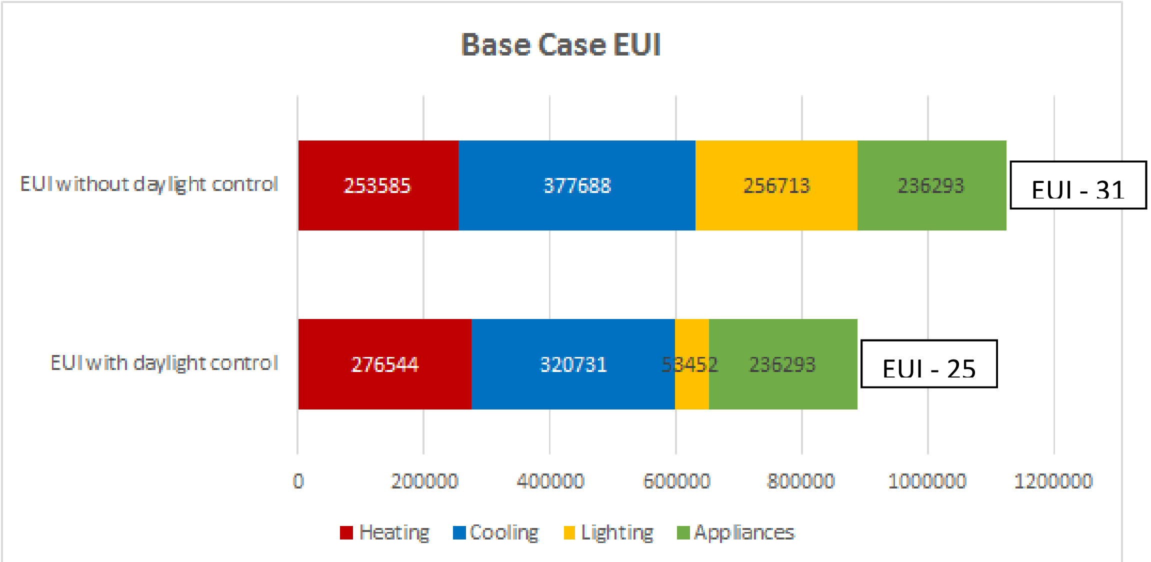


Figure 23: Daylight and glare optimization

Although the EUI does not appear to vary much when the benefits of daylight are not considered, the use of daylight controls involving automatic blinds and continuous dimming of electric lights reduces the EUI from 31 kBTU/sf/yr of the baseline to 24 kBTU/sf/yr of the optimized case with daylight controls (29 kBTU/sf/yr without daylight controls) as shown in Figure 24, thereby achieving the 2030 Challenge (target EUI of 27 kBTU/sf/yr) using just passive design strategies. It can be noted that the use of daylight controls increases the heating load due to the reduction in heat produced by the electric lights, but it also decreases the cooling and lighting loads substantially with lower electric lights usage thereby reducing the overall EUI.



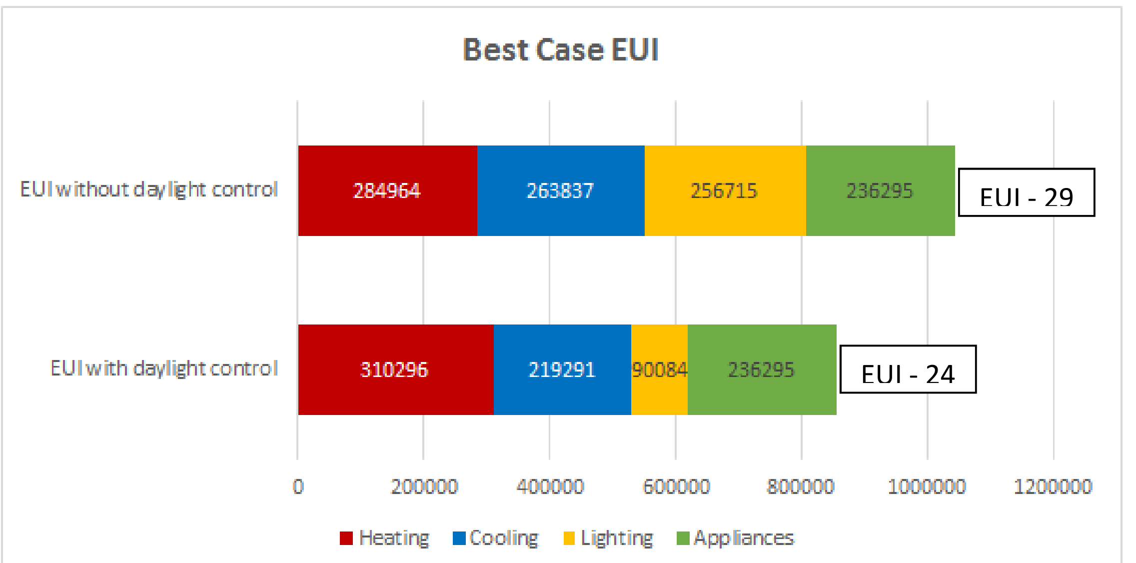


Figure 24: EUI comparison between base case and best case

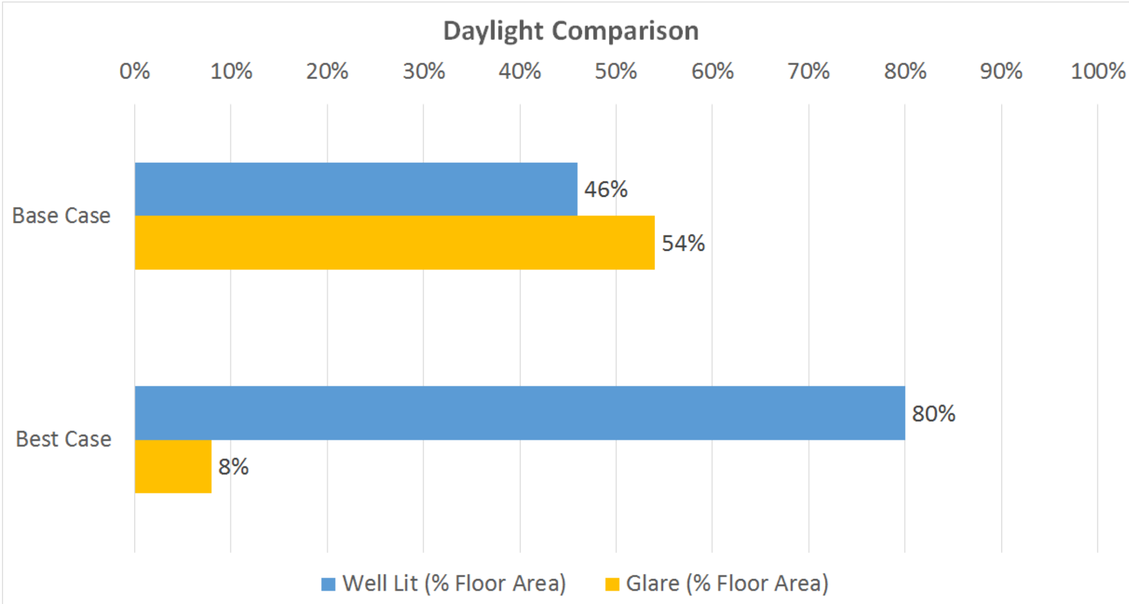


Figure 25: Daylight comparison between base case and best case

Parameter	Base Case	Best Case
Orientation	0 degrees east-west	22.5 degrees east-west
Number of Stories	4	3
Aspect Ratio	2.67	3
Floor to Ceiling Height	13’	12’
WWAR - North	65.4%	90%
Sill Height - South	3.5’	0.5’
Shading Projection - South	0% of window height	100% of window height
WWAR - South	65.4%	60%
WWAR - West	23.1%	10%
WWAR - East	23.1%	20%
Sill Height - West	9’	3’
Sill Height - East	9’	6’
Shading Projection - West	0%	0%
Shading Projection - East	0%	0%
Shading Projection - North	0%	*Doesn’t matter*
Sill Height - North	3.5’	*Doesn’t matter*

Figure 26: Base Case vs Best Case Parameters

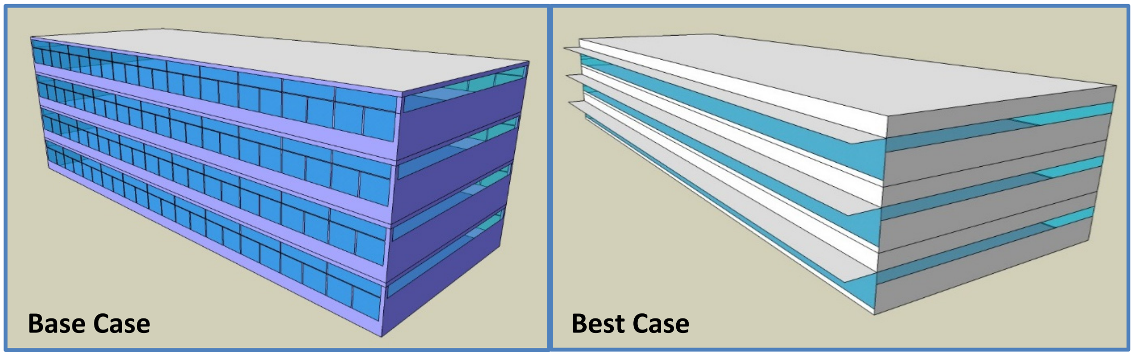


Figure 27: Base case and Best case shoebox models

The daylight autonomy (percentage of annual daytime hours that a given point in a space is above 300 lux) on the third floor is shown below for both base case and best case. It can be seen that the central core space in the best case is not adequately lit for most of the occupied hours, making it an ideal location for service areas like elevator shafts, mechanical rooms and storage. However, the daylight autonomy visualizations do not indicate which areas receive excess glare-causing daylight (>1000 lux) hence limiting their usage in zoning spaces.

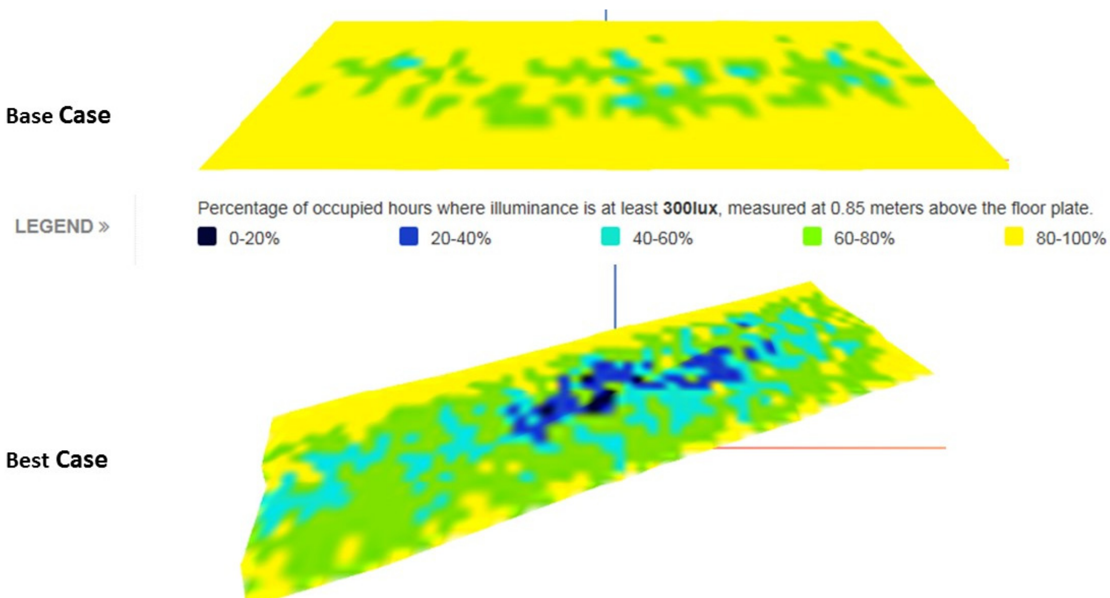


Figure 28: Daylight autonomy comparison

Finally, the best case is compared against the base case in terms of the actual daylight distribution on the floor plates, the depth of daylight penetration into the floor plate, and under-lit areas of the plan to determine basic zoning of spaces. The illuminance levels on the third floor under clear sky conditions at three times of the day on solstices and equinoxes are shown in Figure 29 for both base case and best case. It can be seen that the illuminance levels are reduced in the best case over the base case, thereby resulting in more well-lit interior spaces (400-800 lux) in March and June but more under-lit interior spaces (<400 lux) in September and December. This suggests that the parameters are not necessarily optimized seasonally during the annual optimization of well-lit spaces.

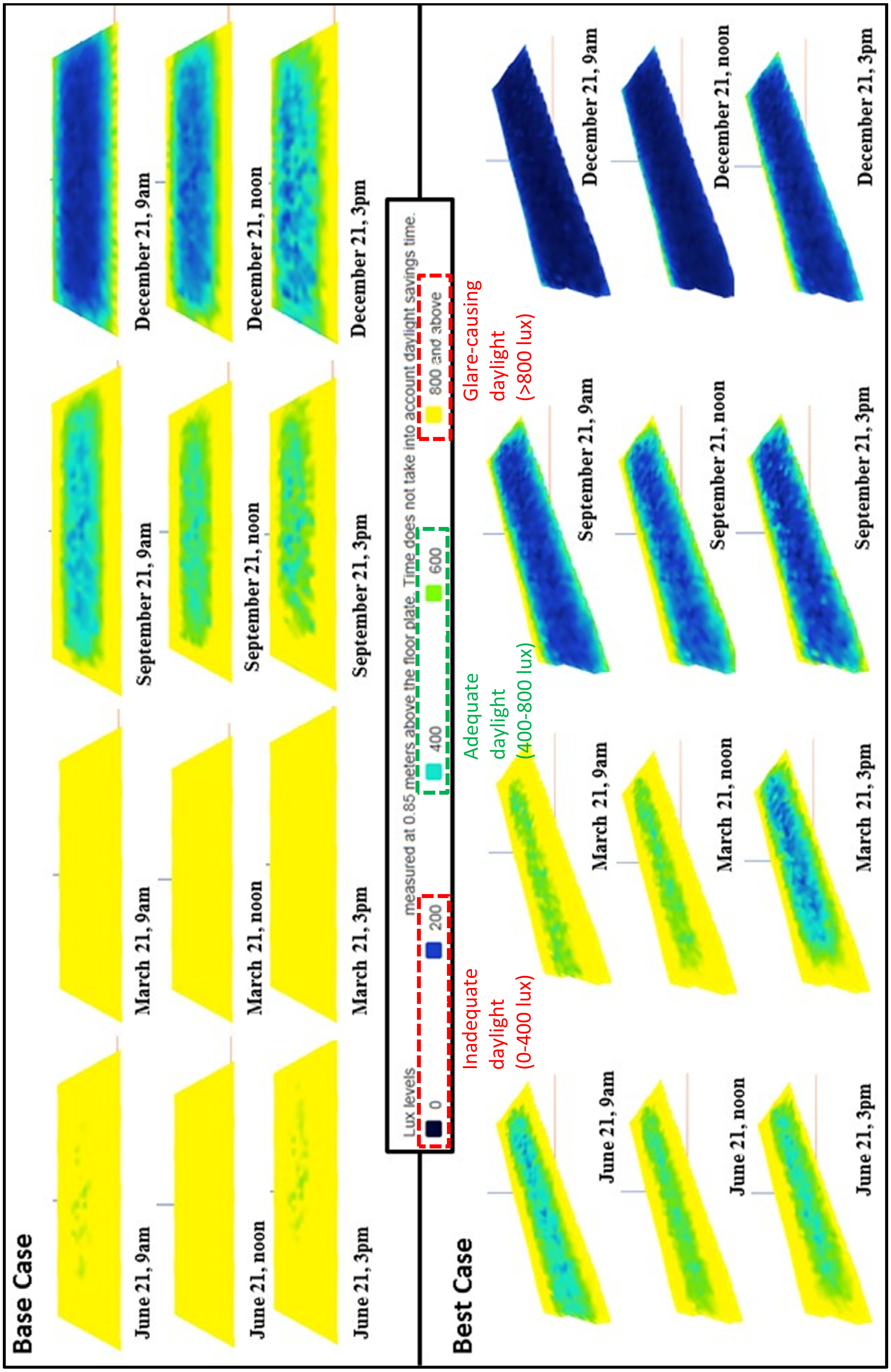
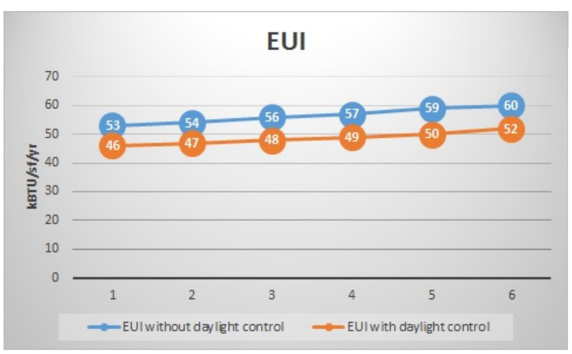


Figure 29: Illuminance Levels on the Third Floor – Base Case vs Best Case

CONCLUSION

The results of the optimization indicate that the order of priority of the parameters produced the desired result by achieving all three goals set earlier – achieving 2030 Challenge, gain LEED points for maximizing sDA beyond 75% and minimizing glare below 10%. Also the biggest players affecting daylight, namely, orientation, number of stories, aspect ratio and floor to ceiling height are also the ones that are usually expected to affect heating load dominated buildings the most, hence reaffirming their importance. Most of the results confirm with rules of thumb in general, but the exact optimized value for each parameter could only be determined by using performance analysis, thereby suggesting that it should be an integral part of the architect's design workflow. Some parameters do not seem to agree with rules of thumb mostly because each building is unique based on its climate and context.

Although the results of the methodology are highly dependent on the specific base case chosen, it can be safely admitted that such process should also work for different climate, surroundings/context and base case properties. The order of priority of parameters would be different for a different climate depending on whether it is heating dominated or cooling dominated (which affects the EUI), and also on the exact geographic location (which affects the sun angles). Surrounding buildings and context would play an important role in determining the optimum parameters as those would affect shading and daylight. A different set of base case properties would result in lower or higher sensitivities to each parameter but the overall order of priority should be the same for the same physical form of the building. For example, by running the aspect ratio parametric analysis on the base case using the default settings provided in Sefaira plugin (Figure 30), the percentage improvement in EUI of the best case over the worst case is (52-46)/52=11.54% as opposed to 17.86% (Figure 21) when using ASHRAE 90.1 2013 baseline (Figure 3).



BASELINE: Default

- Wall Insulation - R-15.77
- Floor Insulation – R-15.77
- Roof Insulation – R-15.77
- Glazing U-Factor - 0.42
- VLT – 0.42
- SHGC – 0.6
- Heating Efficiency – 1 COP
- Cooling Efficiency – 3 COP
- Infiltration Rate – 0.53 cfm/sf
- Ventilation Rate – 0.2 cfm/sf
- Appliance – 1.39 W/sf
- Lighting – 1.11 W/sf

Figure 30: Aspect Ratio EUI Parametric Analysis (left) using default settings (right)

Other passive design strategies like vertical shading on the north, interior light shelves to redistribute light, different glazing and shading patterns could be tested as different parameters and included in the process of determining the order of priority as seen fitting with the architect's specific project requirements. This study could also be extended further to test different building shapes/massing. The optimized values of the parameters obtained in the process could be used as a basis for developing the design in further detail in the next design stages.

The daylighting analysis performed using this methodology in Sefaira results in annual optimization of well-lit spaces (based on sDA) rather than seasonal optimization (Figure 29) thereby limiting its applicability to appropriately zone spaces based on optimal illuminance levels and quality of daylight at particular times of day in a year. Also, the relationship between the annual daylighting analysis (Figure 28) and point-in-time daylighting analysis (Figure 29) is not very self-intuitive, i.e. optimized annual daylighting metrics (sDA and ASE) do not necessarily result in optimized seasonal daylight levels. While certainly critical in architectural design, such an extensive seasonal analysis might not be practical during the early conceptual design phase where quick design decisions are the key, and can therefore be pushed to the design development phase where more detailed analysis are conducted. Sefaira is merely used as an indicator in this methodology to determine whether a design parameter increases or decreases daylighting in general on an annual basis.

This study is intended to produce relative and approximate results rather than absolute results as it is applicable to the conceptual design stage where exact design inputs are not available. Hence the rigor of the software is not the primary concern as much as its processing speed for quick results as long as its based on reliable engines. This technique is used to give the designer directions of which of their design interventions are the most effective to attain their goals. Since this paper is application-oriented rather than software-oriented, any software that is explicitly designed for conceptual design stage and can successfully implement the methodology would be appropriate. A validation study is not included in this paper as most of the previous published research (Hygh et al., 2012) on sensitivity analysis in building performance prediction is focused primarily on sensitivity to changes in energy use while this paper is mainly focussed on sensitivity to changes in well-lit floor area.

In conclusion, this paper discusses one way of setting goals and devising a methodology that is specific to achieving those. Different set of goals require different methodologies, but the ultimate objective of this paper is to promote the use of similar methodologies and tools that architects could integrate into their workflows without losing much time and effort.

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